Challenges in Sustainability

Volume 1 (2013) | Issue 2
Basel, Switzerland

librello

Challenges in Sustainability | 2013 | Volume 1 | Issue 2

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Cover image
A social entrepreneur on his way out to sell improved cookstoves to rural regions of Nyanza Province, Kenya.
Photographer: Ann Åkerman, 2012.

About *Challenges in Sustainability*

Objectives

Challenges in Sustainability (CiS) is an international scientific journal dedicated to the publication of high-quality research articles and review papers on all aspects of climate/global change and transitions towards sustainability. The objective of the journal is to publish important and path-breaking original science in these fields which stimulates the development of solutions in an era of climate and development crisis. System oriented views which integrate relevant issues and help to learn from singular cases are preferred. All manuscript needs to be prepared in English and will undergo a rigorous peer review process. It is the aim that all papers will immediately appear online after acceptance.

Topics to be covered by this journal will include, but are not limited to:

- Environmental and Resource Science
- Climate and Global Change
- Solutions for the Climate Crisis
- Sustainable Cities
- Overexploitation of resources
- Carbon accounting
- Efficiency of carbon offsetting
- Transition Options and Transformation pathways
- Earth System and Integrated Modelling
- Climate Change and Development Economics
- Sustainable Development
- Impact Assessment
- Remote Sensing and Geoinformation

Aims & Scope

The journal defines its place at the interface between natural, socio-economic science and aims to provide a platform which helps to establish systematic analyses on global and climate change problems, associated solutions and trade-offs. In this regard the journal will establish an academic discipline which paves to road towards a deeper understanding of sustainability changes, for option finding and problem solving. Thus, it bridges gaps between disciplines and science and stakeholders while not neglecting scientific rigorousness and excellence. The journal promotes science based insights of the coupled man-environment dynamics and is open for innovative approaches that stimulate scientific and political debates.

Challenges in Sustainability

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DOI: 10.12924/cis2013.01020053

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Research Article

Assessing the Climate Impacts of Cookstove Projects: Issues in Emissions Accounting

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Submitted: 12 April 2013 | In revised form: 10 July 2013 | Accepted: 30 July 2013 |
Published: 17 September 2013

Abstract: An estimated 2.6 billion people rely on traditional biomass for home cooking and heating, so improving the efficiency of household cookstoves could provide significant environmental, social and economic benefits. Some researchers have estimated that potential greenhouse gas emission reductions could exceed 1 billion tons of carbon dioxide equivalent (CO_2e) per year. Carbon finance offers a policy mechanism for realizing some of this potential and could also bring improved monitoring to cookstove projects. However, there are formidable methodological challenges in estimating emission reductions. This paper evaluates the quantification approaches to three key variables in calculating emission impacts: biomass fuel consumption, fraction of non-renewable biomass, and emission factors for fuel consumption. It draws on a literature review as well as on interviews with technical experts and market actors, and identifies lessons learned and knowledge gaps. Key research needs identified include incorporating accounting for uncertainty; development of additional default factors for biomass consumption for baseline stoves; refinement of monitoring approaches for cookstove use; broadened scope of emission factors used for cookstoves; accounting for non-CO_2 gases and black carbon; and refinement of estimates and approaches to considering emissions from bioenergy use across methodologies.

Keywords: carbon market; carbon accounting; household energy

1. Introduction

Globally around 2.6 billion people—40% of the world's population—still rely on traditional biomass (wood, crop residues, dung, etc.) to meet household cooking needs [1]. Nearly three-quarters of these biomass users are in developing Asia, one-quarter in Africa, and the rest in Latin America and the Middle East; in some countries, such as Ethiopia, the Democratic Republic of Congo, Tanzania, Uganda and Bangladesh, over 90% of the population relies on these traditional cooking fuels [1].

Indoor air pollution from the use of open fires and smoky stoves is a major health hazard, responsible for an estimated 2 million deaths per year, and now believed to exceed the combined health burdens of malaria, tuberculosis and HIV [2]. Fuelwood collection can also pose risks to personal safety and keeps women and children away from school or income-producing work, and it puts significant pressure on forests and scrubland. Moreover, traditional biomass burning produces greenhouse gases (GHGs) and black carbon, contributing to climate change.

B_y reducing these risks and pressures, improved cookstoves can yield numerous health, economic and environmental benefits. Moreover, cookstove projects can provide employment opportunities, both making and selling new stoves, and can contribute to technology transfer [3,4].

Cookstove projects to date have drawn on a wide range of public and private sources of finance. Major international sources have included the Global Environment Facility, carbon funds administered by the World Bank and the International Finance Corporation, and Climate Investment Funds. Most recently, the Global Alliance for Clean Cookstoves, a public-private partnership launched in 2010 and managed by the UN Foundation, has set a goal of bringing clean cookstoves and fuels to 100 million households by 2020 [5].

Still, attracting sufficient finance, especially for large-scale cookstove projects, has been difficult. This has led some to suggest a "new" potential solution to this "old" problem: monetizing the emission reduction benefits of improved cookstove projects to attract carbon-market finance (see, e.g., [6]). Several projects have already achieved this, through the Clean Development Mechanism (CDM) under the United Nations Framework Convention on Climate Change (UNFCCC) and other market mechanisms, but much more could be done.

The global technical potential for GHG emission reductions from improved cookstove projects has been estimated as 1 gigaton of carbon dioxide (1 Gt CO_2) per year, with estimates of offsets generated ranging from 0.5–2 tCO_2 per year [3,7]. The low relative cost of abatement, combined with the strong co-benefits for rural livelihoods and the environment, has provided a strong rationale for targeting these project types [8]. The minimum break-even price for Certified Emission Reductions (CERs) under the CDM range from $3–12 per CER depending on the reductions achieved per stove [7]. These estimates make such projects attractive when offset prices are expected to stay above $10 per t$CO_2$e. Such price levels were achieved for voluntary Verified Emission Reductions (VERs) under the Gold Standard and Certified Emission Reductions (CERs) under the CDM for several years (2009–2011), before prices collapsed to about $1 in late 2012 for CERs and ~$5 for high quality Gold Standard credits. Thus the viability of carbon-market finance for cookstove projects will depend on the viability of the markets themselves, which in turn is driven by demand for offset credits by emitters meeting mandatory and voluntary GHG emission reduction targets of varying ambition. If prices remain below the marginal cost of the projects themselves, finance sources other than the carbon market may be needed.

Another consideration is that although CDM projects are meant to serve dual objectives—both emission reductions and sustainable development—serious questions have been raised about how well CDM projects actually deliver on their sustainable development objectives [9–16]. In part to address those concerns, and to focus investment in regions with the greatest development need, for projects registered after 2012, the European Union Emissions Trading System (EU ETS) will only accept CERs from CDM projects hosted in Least Developed Countries (LDCs) [17]. Offset program administrators have noted that the new EU policy could significantly shift the CDM project portfolio. While this could provide new opportunities for improved cookstove projects in LDCs, there is also a considerable need for such projects in more-developed countries such as Kenya, Nigeria and India, where 80%, 74%, and 66% of the population, respectively, still relies on traditional biomass for cooking [1].

Assuming that these challenges can be overcome, there is still a significant barrier that cookstove projects must surpass in order to access carbon-market finance and to ensure environmental integrity: they need credible, scientifically robust methodologies to measure and verify their emission reductions. This paper reviews existing carbon market methodologies for improved cookstove projects, drawing on a literature review as well as interviews with market actors and technical experts, including project developers, offset program administrators, cookstove engineers, and researchers. Interviews followed a semi-structured interview format, with all interviews conducted over the phone using a standard interview guide developed in advance with questions and themes to be explored. Based on this review, we identify key knowledge gaps and areas for additional research that can help to accelerate the development and implementation of improved cookstove projects, and the local and global benefits they can bring. While this paper focuses on project-based offset methodologies, the findings will also be relevant for other carbon finance mechanisms such as Nationally Appropriate Mitigation Actions (NAMAs), broader sectoral crediting mechanisms, or non-crediting mechanisms that involve quantification of GHG benefits.

2. Review of Current Carbon Market Activity

Carbon offsets play a role in both compliance and voluntary carbon markets. In compliance markets, such those created by the Kyoto Protocol or the EU Emissions Trading System, governments and regulated facilities have mandatory, legal emission obligations, and can use offsets, such as CERs, as an alternative to reducing their own emissions. The CDM is currently the only program that can issue offsets from developing countries for use in compliance markets. In contrast, voluntary market offset programs such as the Gold Standard (GS), the American Carbon Registry (ACR), and the Verified Carbon Standard (VCS) issue offsets that can be used by businesses, governments, non-governmental organizations, and individuals electing to offset their emissions for other reasons, such as corporate or individual social responsibility.

All four of these programs (and no others) have enabled crediting of emission reductions from improved cookstove projects. Each has approved methodologies or protocols that specify eligible technologies and project types, and the means by which projects are monitored and their emission reductions quantified. The methodologies apply to projects that are introducing a stove technology and consider the emissions savings from reducing or displacing the use of non-renewable biomass for household heating and cooking. Here we define non-renewable biomass as biomass production that is not sustainably managed and results in a decrease in carbon stocks over time [18].

Under the CDM, two methodologies are available. AMS II.G applies to cases where an improved-efficiency cookstove is introduced to reduce the demand for non-renewable biomass. AMS I.E applies to cases where a renewable technology, such as biogas or solar cookers, is introduced to displace use of non-renewable biomass. Note the AMS I.E methodology is considered here because the baseline scenario approach is very similar to AMS II.G. However, the project scenario approaches under AMS I.E of introduction of new renewable energy technologies are not explored in this paper. The Gold Standard allows project developers to use one of the two CDM methodologies as long as they meet additional stakeholder consultation and sustainable development co-benefit requirements. The Gold Standard also has its own methodology that applies to projects that decrease or displace GHG emissions from thermal energy consumption in households or non-domestic facilities, but unlike the CDM methodologies, may include improved fossil fuel (in addition to improved biomass) technologies [19]. The American Carbon Registry's cookstove methodology is a modified version of AMS I.E, with expanded applicability and modified calculation and monitoring methodologies. The Verified Carbon Standard does not have its own cookstove methodology, but allows the use of approved CDM methodologies. Table 1 outlines the specific methodologies and applicable versions evaluated in this paper, which are discussed in greater detail in Section 3.

Nearly all improved-cookstove offset projects are registered or in the project pipeline under either the Gold Standard or the CDM. As shown in Figure 1, approved and under-development cookstove projects are expected to yield more than 10 million offset units over their first crediting periods (7 or 10 years). To date no projects have been developed under the American Carbon Registry, and only one project, using the CDM methodology AMS I.E., has been developed under the Verified Carbon Standard, in Cambodia.

Even though over half of the projected volume of credits generated will be CERs under the CDM, the Gold Standard plays a pivotal role in the market for cookstove offsets. Close to 40% of projected CERs generated under the CDM also aim to be certified under the Gold Standard. These projects have been developed using the CDM methodology and have applied the additional Gold Standard stakeholder and sustainable development requirements to receive Gold Standard certification. This is distinct from projects which have been developed using the standalone Gold Standard improved cookstove methodology. Together, Gold Standard Verified Emission Reductions (VERs) and Gold Standard-certified CERs account for over three-quarters of the offsets projected to be generated from improved cookstove projects. That the vast majority of cookstove projects have achieved this additional certification demonstrates the perceived added value of Gold Standard label, and its associated stakeholder and sustainable development processes.

The geographic distribution of cookstove projects is notable. While across all project types in the CDM pipeline, less than 5% of credits are generated from projects in Africa, over 65% of emission reductions from improved cookstove projects are based in Africa (see Figure 1). The Asia and Pacific region, which makes up close to 80% of the total CDM pipeline across all project types, comprises only 30% of improved cookstove project types [20]. Just 4% of emission reductions from improved cookstove projects are based in Latin America (Figure 1).

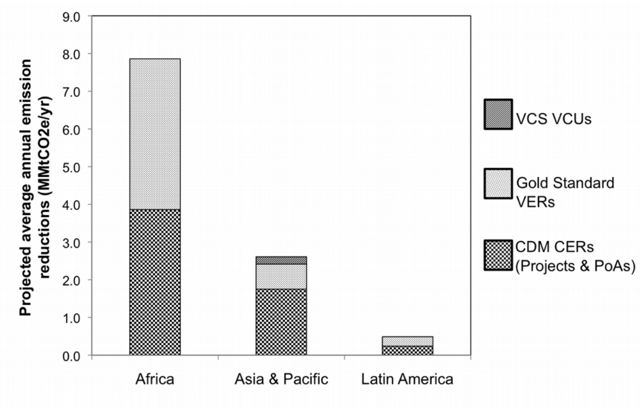

Figure 1. Projected average annual offset volume of projects accepted and under development across programs.
Note: data are projected offset volumes based on estimates in project design documents. Data include projects categorized as household energy efficiency projects. We include CDM registered, registration requested or at-validation projects that apply either the AMS II.G and/or I.E methodologies [20]. We include Gold Standard VERs projections from issued, registered, validated or listed projects [21]. We include registered and issued VCS projects, per the VCS Projects Database, [22].

These trends follow estimates of per capita fuelwood consumption, which are considerably higher in Africa than in Asia and South America [23].

Close to half of the projected CERs from projects in Africa come from five countries: Burundi, Zambia, the Democratic Republic of Congo, Ghana and Kenya. Well over half of the CERs from the Asia and Pacific region come from India, Nepal and Pakistan. In Latin America, the largest projects under development are in El Salvador and Honduras. Mueller et al. (2011) found Benin, Burkina Faso, Cambodia, Mali, Mozambique, Niger, and Zambia to be among the countries best-suited to improved cookstove projects based on an assessment of charcoal production and consumption, deforestation rates, the percentage of total national energy consumption that is met by traditional biomass, and the interest from host country agencies in encouraging cookstove projects.

With a geographical shift in focus to projects developed in LDCs (to meet the EU ETS' acceptance of only CERs generated in LDCs after 2012), it is worth noting that already nearly half of all household energy CERs accepted and under development under the CDM come from LDCs [20]. In contrast, under the Gold Standard, only 10% of the projected offsets (VERs) issued are from LDCs [21]. Most of projected African VERs are from non-LDC countries: Kenya, Nigeria and South Africa.

Household energy efficiency projects (including improved cookstove projects) make up only 1.2% of CDM projects in the pipeline and are expected to produce less than 0.5% of CERs issued per year. However, this could change with the refocus on LDCs in the EU ETS after 2012.

As shown in Figure 2, the number of projects, both individual and Program of Activities (PoAs), has increased considerably since methodologies were first approved in 2008. A PoA is a "voluntary coordinated action by a private or public entity which coordinates and implements any policy/measure or stated goal (i.e. incentive schemes and voluntary programmes), which leads to anthropogenic GHG emission reductions or net anthropogenic greenhouse gas removals by sinks that are additional to any that would occur in the absence of the PoA, via an unlimited number of CDM programme activities" [24]. PoAs represent an aggregated approach that enables multiple project activities to be registered through a single approval process, offering lower transaction costs and increased scalability. Because of their larger size, PoAs are expected to deliver the large majority (over three-fourths) of cookstove CERs. Despite the increased project development activity, registration of projects and issuance of credits has been limited. To date only 11 individual, and no PoA, cookstove projects have been registered and just over 54,000 CERs have been issued [20]. Furthermore, the average issuance success rate of these projects has only been 20%, in comparison to credit volumes projected in project design documents [20].

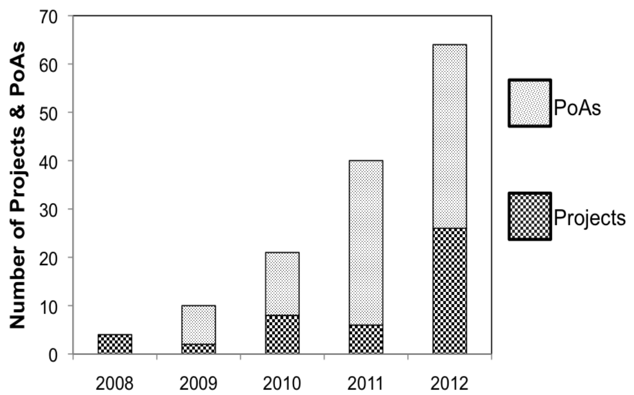

Figure 2. Number of CDM projects and PoAs submitted each year since methodologies (AMS I.E and AMS II.G) were approved in 2008.
Note: projects include those applying either the AMS II.G or I.E methodologies. Years are approximated using the start date of the public comment period under validation. Source: UNEP Risoe Centre [20].

Table 1. Improved cookstove carbon crediting methodologies reviewed.

Program	Gold Standard	CDM (and VCS)–AMS II.G	CDM (and VCS)–AMS I.E	ACR version of AMS I.E.
Methodology version reviewed	Version 1.0, 11/04/2011 [19]	Version 05 UNFCCC [25]	Version 05 (UNFCCC 2012a)	April 2011 [26]
Applicability	Introduction of technologies/practices that reduce or displace GHG emissions from thermal energy consumption by households, institutions, commercial or industrial premises	Introduction of high-efficiency thermal appliances utilizing non-renewable biomass or retrofitting existing units to reduce the use of non-renewable biomass	Introduction of renewable energy technologies that displace the use of non-renewable biomass	
Measure of biomass fuel consumption	Kitchen Performance Test (KPT)	Three options: Kitchen Performance Test (KPT), Water Boiling Test (WBT), or Controlled Cooking Test (CCT)		
Fraction non-renewable biomass	Quantitative assessment based on estimates of mean annual increment (MAI) and woody biomass harvest for the area where fuel is collected; or qualitative assessment based on satellite imagery and field surveys; follow CDM AMS II.G	Project-specific surveys or default f_{NRB} values for LDCs, Small Island Developing States (SIDS) and countries with less than 10 registered CDM projects as of 31 December 2010. based on national-level assessment of mean annual increment (MAI) and total harvest		
Baseline scenario	Typical baseline fuel consumption patterns in target population adopting the project technology	Assume use of fossil fuel to meet demand for cooking/heating	Assume use of fossil fuel to meet demand for cooking/heating	
GHGs included in project boundary	CO_2, methane (CH_4), nitrous oxide (N_2O)	CO_2	CO_2	
Project types covered	Adoption of project technology to reduce fuel consumption in target population	Installation of more-efficient thermal appliances to reduce use of non-renewable biomass	Use of renewable energy technologies for thermal energy to displace the use of non-renewable biomass	
Additionality	Either CDM additionality tool [27], CDM small scale project guidelines (as for AMS-II.G and I.E) [28], or demonstration that technology is "first of its kind" (< 20% adoption rate in target area)	Either:1) located in LDC/SIDS or special designated under developed zone of host country [28]; 2) annual energy savings are less than 600 MWh and end users are households/communities [28]; 3) each unit is no larger than 5% of the small-scale CDM threshold (750 kW installed capacity or 3,000MWh energy savings per year or 3,000 metric tons emission reductions per year), and end users are households/communities [28];		
Leakage	Methodology specifies several potential sources of leakage to be investigated. If found that non-project households increase their fuel consumption as a result of the project, then calculations must be adjusted.	Must consider the increase in the use of non-renewable woody biomass by non-project households through ex-post surveys of users and the areas where non-renewable woody biomass is sourced. If it is found that use increases, the estimate of quantity of wood saved must be adjusted.		

3. Three Key Parameters in Improved Cookstove Methodologies

This paper reviews the methodologies currently available for crediting emission reductions from improved cookstove projects. Table 1 below compares the various program features of the pertinent CDM, Gold Standard, VCS, and ACR methodologies. These improved cook-stove methodologies fall under one of two types: improved energy efficiency (e.g., CDM's AMS-II.G) or fuel switching to renewable energy (e.g., the CDM's AMS-I.E). ACR's cookstove methodology adapts AMS-I.E. and focuses on fuel switching. VCS allows use of CDM methodologies and thus applies to both project types. The Gold Standard methodology could apply to both improved efficiency and fuel switching, though this paper focuses on the efficiency projects.

Projects that focus on improving the energy efficiency of cookstoves (using AMS-II.G) account for nearly 80% of CDM cookstove projects, over two-thirds of the cookstove offsets issued to date (see Figure 1). To give a sense of typical CDM projects, one Nigerian project involved distribution of up to 12,500 efficient wood stoves in the Guinea Savannah Zone, where deforestation has become a concern (e.g. [29]). The Turbococinas rural cooking stove substitution PoA in El Salvador [30]—where the use of fuelwood for cooking has helped drive some of the worst deforestation in Latin America—distributed over 100,000 stoves that were designed to use small pieces of wood from tree trimmings which avoids cutting down whole trees.

While less common than stove efficiency projects, several CDM projects have involved a switch from non-renewable biomass fuel to renewable sources (using methodology AMS-I.E). In Zambia, for example, one CDM project involved switching from stoves using non-renewable charcoal to stoves using small sticks from renewable biomass sources in 30,000 households in Lusaka City [31]. In rural Rwanda, a CDM project introduced four solar photovoltaic water treatment plants to displace the use of non-renewable fuelwood to boil water [32]. The CDM-supported Biomass Support Program in Nepal distributed 20,000 biogas stoves and digesters to displace use of non-renewable firewood [33].

In both types of cookstove projects—improved efficiency and fuel substitution—emission reductions are calculated as the product of the amount of woody biomass saved, the fraction that is considered non-renewable biomass, the net calorific value (NCV) of the biomass, and an emission factor for the fuel used. The CDM methodologies AMS II.G and AMS I.E provide the following equation for calculating emission reductions:

$$Er_y = B_y \times f_{NRB,y} \times NCV_{biomass} \times EF_{proj.fossilfuel} \quad (1)$$

Where:

ER_y = Emissions reductions during year y in tCO_2e

$B_{y,}$ = Quantity of woody biomass saved (or substituted or displaced), in tons

$f_{NRB,y}$ = Fraction of woody biomass saved by the project activity in year y that can be established as non-renewable biomass

$NCV_{biomass}$ = Net calorific value of the non-renewable woody biomass that is substituted (Intergovernmental Panel on Climate Change default for wood fuel, 0.015 TJ/ton)

$Ef_{proj\_fossilfuel}$ = Emission factor for the substitution of non-renewable woody biomass by similar consumers.

The methodologies follow similar approaches regarding evaluation of the project scenario, additionality and leakage, as shown in Table 1. Consequently, these parameters are not addressed in further detail here. Since the net calorific value of the non-renewable biomass ($NCV_{biomass}$) is relatively straightforward—it is empirically measurable and a default value from the Intergovernmental Panel on Climate Change (IPCC) exists—this variable is also not considered further.

Methodologies differ in their approaches to three primary inputs required for calculation of the emission reductions from this project type: biomass fuel consumption (B_y), fraction of non-renewable biomass (f_{NRB}), and emission factors for fuel combustion ($Ef_{proj\_fossilfuel}$; Table 3). The method and assumptions used in estimating each of these variables contributes to uncertainty in the calculation of emission reductions. A study by Johnson et al. (2010) [34] assessed the relative contributions of the three variables to the overall uncertainty in carbon offset estimation for an improved cookstove project in Mexico. The study found that fuel consumption (B_y) contributed to 28% of the uncertainty, while the fraction of non-renewable biomass (f_{NRB}) contributed 47%, and emission factors ($Ef_{proj\_fossilfuel}$) accounted for 25%.

In the following sub-sections, we focus on the quantification of these three parameters:

- Estimating biomass fuel savings (Section 3.1);
- Assessing of the impact of biomass consumption on above-ground carbon stocks (Section 3.2); and
- Estimating CO_2 emissions from cookstoves (Section 3.3).

Table 2. Comparison of biomass fuel consumption testing approaches.

Test name	Type of test and what it measures	Strengths	Weaknesses
Kitchen Performance Test (KPT)	Community test (in households); measures fuel use in households based on normal cooking tasks over several days. The approach using the KPT simply subtracts the quantity of woody biomass used by project participants (based on a random sample) from the amount of biomass used by a representative sample of non-participant households. Both are measured over a three-day period. Total biomass available in the household is weighed at the start and end of each day or meal to measure the weight of fuel used.	Typically conducted in actual stove dissemination effort with local cooks. Best way to understand stove's impact on fuel consumption, as well as household characteristics and behaviors as it occurs in the user's household. Provides a consistent approach for estimating both baseline and project biomass consumption.	Measurements more uncertain as possible sources of error are difficult to control compared with laboratory tests.
Water Boiling Test (WBT)	Laboratory test; assesses stove performance while completing a standard task (boiling and simmering water). The approach relying on the WBT calculates the biomass savings based on the amount of biomass used in the absence of the project, and the relative efficiencies of the new and replaced stoves. The efficiency of the system being replaced is measured with representative sampling methods, published values or default values. Efficiency of the new system being deployed under the project activity is determined by the WBT. Data for improved stoves is provided by the stove manufacturer.	Simple method that can be performed on most stoves worldwide (standardized and replicable). Provides a preliminary understanding of stove performance, useful during design.	Reveals technical stove performance, not necessarily what can be achieved in actual households while cooking actual foods. Relies on default values for baseline cookstove biomass consumption.
Controlled Cooking Test (CCT)	Laboratory test, performed by a local cook on location or in-field in a test kitchen; measures stove performance using actual local cooking methods as a cook prepares a typical meal intended to be representative of cooking practices of the target population participating in the project. The approach using the CCT calculates the biomass savings based on the relative specific fuel consumption or fuel consumption rates of the baseline and replacement systems. The fuel consumption rate (fuel consumed per item processed (e.g. food cooked) or per amount of time) is determined by using the CCT.	Stoves are assessed while performing a standard cooking task (more closely mimics actual cooking done by local users). Test design helps minimize influence of potential confounding factors and allows for conditions to be reproduced.	Demonstrates what is possible under ideal conditions, but not necessarily what occurs under daily use.

Sources: [35-37].

3.1. Estimating Biomass Fuel Savings: B_y

The amount of woody biomass saved, defined as the reduction in biomass consumption with the introduction of an improved cookstove (either through efficiency gains or fuel switching), is one of the key data inputs for quantifying emission reductions from projects and is a source of uncertainty for project developers. Under CDM methodologies AMS II.G and AMS I.E, the quantification of emission reductions (see Section 3) relies on the factor $B_{y,}$, representing the "quantity of woody biomass that is saved" or reduced by the project activities [25, 38].

CDM methodology AMS II.G presents project developers with three options for quantifying biomass fuel savings from improved stoves: the Kitchen Performance Test (KPT), the Water Boiling Test (WBT), and the Controlled Cooking Test (CCT). Table 2 describes each of these methods, along with their strengths and weaknesses. In contrast to the other two laboratory-based methods, the Kitchen Performance Test is done in the field, and can thus better represent stove users' actual cooking behaviour. The Gold Standard methodology only allows the use of the KPT. However, KPT measurements are subject to large uncertainties as, compared with laboratory tests, it can be difficult to control sources of error. The primary advantage of the Water Boiling Test is its simplicity; the laboratory-based method is standardized and replicable. However, the laboratory results on stove performance do not necessarily translate to cooking actual meals in households, and thus the accuracy of this method is frequently called into question. Meanwhile, the Controlled Cooking Test protocol provides a compromise, better representing local cooking while being conducted in a controlled environment.

For each of these options, the quantity of woody biomass used in the absence of the project is calculated in one of two ways. The first method is using historical data or local surveys of the estimated annual average consumption of woody biomass per appliance. The second method is quantification based on the amount of thermal energy generated by the project, net calorific value of biomass fuel and the replacement system efficiency.

Detailed guidelines for performing each of the tests have been developed and tested in laboratory and field studies. While the CDM methodology allows flexibility in the selection of the stove test, cookstove experts interviewed for this paper expressed concerns about the accuracy of some tests, especially the WBT. As highlighted in Table 2 and Figure 3, there are a number of trades-offs related to accuracy versus degree of complexity and costs. Fuel consumption can be driven by myriad factors (e.g., geography, climate, and cooking practices), making it highly difficult to develop an adequate one-size-fits-all estimation approach [39].

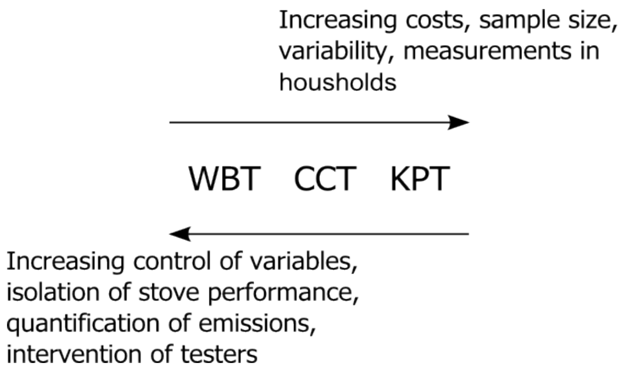

Figure 3. Relative benefits and trade-offs of biomass use quantification approaches.
Source: Adapted from Aprovecho Research Center [39].

Emission factors calculated from water boiling tests do not always reflect household emissions from daily cooking activities [40,41]. Johnson et al. [42] found that under daily-use conditions, improved Patsari stoves developed for use in rural Mexico performed significantly worse relative to open fires in WBT tests than they had in simulated kitchens—but they also performed significantly better in daily use when making tortillas—a far more common activity. Thus the WBT proved inadequate on multiple levels. Berrueta et al. [43], meanwhile, evaluated Patsari stoves using all three tests, and found the WBT "gave little indication of the overall performance of the stove in rural communities". The CCT, focused on tortilla-making, was somewhat more predictive of the fuel savings found by the KPT (44–65% for CCT vs. 67% for KPT). Thus, the researchers concluded, field-testing stoves "is of critical importance" [43]. Experts interviewed for this paper offered a similar perspective; as one put it, if there is a correlation between WBT efficiency measures and stoves' real-life performance, "we haven't yet found it".

Published studies and project developers interviewed generally agree that the KPT is a more robust way to determine whether new cookstoves actually provide fuel savings. Johnson et al. (2010) [34] suggest that although community level sampling requires additional effort and costs, it is also likely to deliver a larger volume of offset credits, which can then more easily absorb the higher transaction costs. However, market actors interviewed noted that most project developers, when using the CDM methodology, use the WBT, because it is cheaper and easier to implement, with default values provided by the stove manufacturer. The decision to use the WBT vs. KPT may also depend on the project size: project developers said that for a larger-scale project or PoA, the KPT is likely to be much less feasible and they are more likely to use the WBT approach. Technical experts also noted that there may be ways to reduce the cost of a KPT, such as having local NGOs perform the tests rather than hiring expensive international consultants.

To the extent that the WBT is still used, it can be improved. Quantification relies on values for baseline fuelwood consumption and for the efficiency of the traditional stove being replaced (this is also true for the CCT). The CDM methodology provides default efficiency values for two traditional stove types—a three-stone fire, or a conventional system with no improved combustion —as well as a default efficiency value for devices with improved combustion air supply or flue gas ventilation. Experts interviewed noted that these limited defaults do not cover the range of cookstoves in most countries. Market actors interviewed suggested developing conservative default values for these parameters to use instead of in-field values, to reduce uncertainty. The CDM Small-Scale Working Group (CDM SSC WG) recently considered doing so, but decided not to proceed because the huge variation in available data estimates made the use of regional default values infeasible [44]. Though more logistically complicated, and time—and source-intensive, testing stoves outside of a controlled laboratory setting and using a variety of typical cooking activities, as is done in the KPT, appears to be an important factor in ensuring accurate and credible results in the baseline or default analysis.

While in some respects, the CCT can be considered a compromise between the less-accurate WBT and more-burdensome KPT, experts still cite a number of issues with this test. As noted above, the CCT is usually done in a simulated kitchen (or at least in the same kitchen as the traditional stove comparison test), and it is generally considered a laboratory test, like the WBT, more controlled than the KPT. However, evaluating one cooking task does not accurately represent stove performance and fuel use in households' actual daily cooking activities. While the CCT does more accurately measure fuel consumption in the performance of particular cooking tasks than the WBT, it cannot easily be compared across regions or types of food [43]. It has been suggested that although the CCT offers benefits of reduced costs from field testing relative to the KPT, these gains are likely outweighed by the added uncertainty in the CCT approach and the potential for corresponding reductions in carbon offsets generated [34].

AMS II.G monitoring requirements include checking the efficiency of the stoves (all, or a representative sample) and confirming at least every two years that the stoves are still in use. Additional stove monitoring is required annually (or biennially if project proponents can demonstrate no significant efficiency losses in the new device), with the specific factor to be monitored depending on which test protocol is used (fuel consumption for the KPT, efficiency for the WBT, and specific fuel consumption for the CCT). One challenge in monitoring is determining the extent to which the new stoves have replaced the old. There is an assumption that new stoves meet all cooking needs, but technical experts interviewed have found that this is "definitely not the case" and results in an overestimation of new stove use. Monitoring under the CDM requires that the traditional stove either be disposed of or not used; otherwise it must be monitored to ensure fuelwood consumption from that stove is excluded from baseline consumption estimates. Monitoring the continued use of traditional stoves is a challenge; technical experts said better alternatives are needed. The KPT test does help address the replacement issue better than the WBT; since the KPT will measure real fuel usage across all stoves used by the household, market actors interviewed have found that it can provide a more accurate picture.

One recent proposal for monitoring stove usage noted by a project developer is the use of data loggers affixed to stoves. Temperature sensors, including the Stove Use Monitoring System, also known as SUMS, developed by Prof. Kirk Smith's research group at the University of California-Berkeley and sold by Berkeley Air, have the potential to more accurately capture data on stove usage. Moreover, several technical experts have noted that combining data logger output with the KPT could generate more comprehensive estimates of fuel consumption. There are still some issues concerning data loggers, such as how to be sure they are truly randomly dispersed among the cookstoves distributed, while at the same time remaining geographically consolidated to facilitate downloading data from loggers locally. Project developers interviewed noted that methodologies do not currently have a mechanism to incorporate data logger information into monitoring.

Program administrators interviewed see great potential in data loggers to address challenges in project monitoring. Managing transaction costs associated with implementation of sampling plans and precision requirements is highlighted as very important for the success of future projects. Regulatory documents, including sampling standards and best practice examples, have been developed for monitoring sampling and surveying. However, program administrators indicated that implementation of monitoring plans continues to pose many challenges for projects and is likely a contributor to the modest issuance success rates observed by projects so far.

In response, a request has been made to the CDM Executive Board by the Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol (CMP) to consider revising the monitoring requirements, including provisions for how to deal with missing survey data. One concern raised is that none of the current methodologies incorporate uncertainties in estimates of fuel usage. Johnson et al. [34] critique the Gold Stan Standard dard and CDM methodologies for not following the Guidelines for National Greenhouse Gas Inventories (Tier III) nor the Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories "by allowing non-representative inputs and not accounting for uncertainty in offset estimates".

Instead, they suggest that IPCC recommendations for uncertainty from the Good Practice Guidance and Uncertainty Management in National GHG Inventories should be applied to project emission reductions calculations [45].

3.2. Assessing of the Impact of Biomass Consumption on Carbon Stocks: $f_{NRB,y}$

Cookstove offset projects are premised on the notion that improved stove efficiency or fuel substitution reduces the use of non-renewable biomass. The factor f_{NRB} represents the "fraction of woody biomass saved by the project activity in year y that can be established as non-renewable biomass" [25], and is a key variable in all current cookstove offset methodologies. Yet determining the fraction of biomass use that a cookstove project will avoid that involves non-renewable biomass is perhaps the most difficult challenge for offset crediting methodologies. How offset methodologies estimate the carbon emissions from biomass combustion stands in contrast to standard emissions accounting approaches, in particular, those established by the UNFCCC used in national inventories. Under these traditional accounting approaches, the combustion of biomass, whether or not it is considered renewable, is considered to have no net CO_2 emissions impact. Instead, the impact of combustion of non-renewable biomass is expected to be manifested in a corresponding long-term reduction in carbon stocks in forests and other lands.

With renewable biomass, trees and plants are expected to ultimately fully regrow, resulting in no net long-term change in atmospheric CO_2 concentrations. In contrast, when biomass comes from forests or non-forest areas that are not sustainably managed, and where deforestation and/or land degradation may be occurring, the CO_2 released through biomass combustion will not be offset by new growth.

Based on its definition of renewable biomass [46], the CDM Executive Board has identified several indicators of scarcity to help identify non-renewable biomass. Woody biomass is considered non-renewable if at least two of the following indicators are shown to exist:

- A trend showing an increase in time spent or distance travelled for gathering fuelwood, by users (or fuelwood suppliers) or alternatively, a trend showing an increase in the distance the fuelwood is transported to the project area;
- Survey results, national or local statistics, studies, maps or other sources of information, such as remote-sensing data, that show that carbon stocks are depleting in the project area;
- Increasing trends in fuel wood prices indicating a scarcity of fuel-wood;
- Trends in the types of cooking fuel collected by users that indicate a scarcity of woody biomass (UNFCCC 2011b; 2012a).

Specific approaches and guidelines for quantifying the fraction of non-renewable biomass vary across the protocols. Until recently, CDM methodologies included only guidance on determining f_{NRB} based on the above definition, but no specific quantification approaches or default factors. The lack of a standardized approach for determining the f_{NRB} value for projects was considered a source of uncertainty for—and a barrier to—project development, by both technical experts and market actors interviewed (see, e.g., [8]).

Across the board, consistent accounting methods are considered critical to demonstrating the credibility of these carbon market projects [8]. A study by Johnson et al. (2010) [34] found that differences in approaches for quantifying f_{NRB} contributed 47% to the overall uncertainty of emission reductions generated for an improved cookstove project in Mexico. The scale of data selected in estimating f_{NRB} can potentially introduce error; for instance, if national-level data are used, as they are for the default values, they may be too aggregated, given potentially wide variations among local communities. According to one technical expert, a survey of CDM cookstove project design documents (PDDs) found that most projects based their f_{NRB} assessment on national-level data on mean annual increment of forest growth and total wood harvest. The survey results also suggested that projects were not consistent in data sources cited; many loosely cited "literature" without referencing specific data sources. Very few conducted their own project-specific survey of f_{NRB}, and on average, the preliminary survey found the f_{NRB} claimed by projects was close to 80% (with 100% being all non-renewable).

As part of the effort to improve and further standardize f_{NRB} assessments, the CDM Executive Board issued a call for public input on two proposed approaches for quantification of f_{NRB} at its 63rd meeting in September 2011: one based on the Woodfuel Integrated Supply/Demand Overview Mapping (WISDOM) methodology, and another based on mean annual increment (MAI). The WISDOM method determines the f_{NRB} at a sub-national level, "by incorporating spatial variations of the biomass and population data for the given geographic areas from which the woody biomass is extracted, their sustainable production capacity and their existing management systems" [47]. The MAI approach determines aggregate country-specific values of f_{NRB} based on the difference between the fuelwood consumption of households and the adjusted MAI of biomass growth [47].

Johnson et al. [34] and Reddy [48] suggest that by generating more localized assessments, the WISDOM model could produce more accurate estimates of f_{NRB}. Johnson et al. [42] suggest that regional or national average f_{NRB} figures based on MAI risk underestimating the carbon emission reductions. Results from Johnson et al. [8] found that for one village in Mexico, a community-scale application of the WISDOM model estimated the f_{NRB} at 85%, while using the WISDOM model to develop a broader regional average [49] resulted in an f_{NRB} of only 20%—not reflective of the situation in the village. Indeed, as Johnson et al. [34] note, the community-level analysis approach supports the targeting of stove projects to communities where biomass scarcity is greatest and the rates of improved cookstoves are likely to be higher.

Despite these advantages, the WISDOM model, as noted by some stakeholders, is a complex tool, with significant data requirements, and the need for many project-specific assumptions [48,50]. Furthermore, the WISDOM model was designed for rural woodstove projects where households gather their own fuelwood. Applicability of the model to urban fuelwood projects is less obvious [51]. Nevertheless, technical experts interviewed suggested that the tool could conceivably be used to simulate impacts on "fuelsheds" used to produce wood fuels (including charcoal) that are transported to urban areas.

In 2012, the CDM Executive Board issued national default factors for f_{NRB} based on a highly aggregated MAI approach [38,52]. Under this approach, the f_{NRB} values were calculated for nearly 100 countries, based on the total annual national biomass removals minus the portion of demonstrably renewable biomass from growth in protected reserve areas. (Note that this approach does not distinguish removals for timber harvesting from those for fuelwood.) The large majority (over four-fifths) of default values exceed 80%, with the remainder ranging from 40% to 77%. Before the default values can be applied by a project, they must be approved by designated national authority of the host county, as of March 2013, only 18 countries had given approved their default values [52].

Several market actors interviewed characterize development of default f_{NRB} values as a "huge triumph", since avoiding the need to establish new f_{NRB} values for each project can greatly reduce project development costs and quantification uncertainty. According to the Executive Board decision, project proponents have the choice of using these "conservative country-specific default values" or determining "project-specific values by undertaking a study in the project region as prescribed in the methodology" [28]. As a result, many project developers are unlikely to incur the added costs of such a study, especially given the high values for most country-specific defaults.

However, despite support for standardized default values, there is recognition by market actors and researchers interviewed that relying on national-level forest growth and total harvest removals may not be appropriate for estimating whether or not fuelwood and wood products in general are renewable. Some project developers said the national-level default values are "too conservative" and do not reflect conditions in the targeted regions where they are operating, and as a result they find it worthwhile to develop their own project-specific values to maximize their emission reduction credits. Others have critiqued the use of national-level estimates given the poor data quality, particularly in LDCs, of UN Food and Agriculture Organization (FAO) forest resource assessments data; they have also noted that national-level estimates cannot account for heterogeneous climatic and geographical conditions that impact fuelwood supply and demand, thus leading to an over—or underestimation of the f_{NRB} parameter [50]. It was also suggested that sub-national f_{NRB} values should be allowed if and when fuelwood consumption data are reported at a sub-national level [48].

Other approaches have been proposed for quantifying the f_{NRB}. The net carbon stock approach compares the household demand for biomass for fuelwood against other possible uses of biomass (e.g. carbon storage, wood products); emissions reductions/removals are calculated as the net change in carbon stocks attributable to reducing fuelwood consumption as compared to the net change in carbon stocks attributable to other uses of wood. Interviewees also noted that new spatially explicit models are under development (e.g. Winrock International's GeoMOD and NRB v1.0, via a collaboration between Yale University and Universidad Nacional Autónoma de Mexico) that consider fuelwood demand and fuel type with dynamic biomass supply sources, as well as incorporating land-use change. Market actors interviewed see integration of alternative quantification approaches to develop sub-national f_{NRB} estimates as an urgent need.

As income rises, households prefer to avoid the drudgery of fuelwood collection and progress to using modern fuels, suggesting to some extent that fuelwood is considered an "inferior good" [23]. However, the suggestion based on default values developed that three-quarters or more of all fuelwood used is not renewable and is directly contributing to deforestation raises a few red flags and deserves some reflection on the history of research on these issues. Following the fossil fuel energy crisis of the 1970s, there was increasing recognition of the reliance of households in the developing world on wood for heating and cooking. Predictions raised the alarm of an impending fuelwood crisis, with massive deforestation and severe impacts on the poor, giving rise to estimates of the fuelwood gap and the urgent need for planting trees to meet projected demand [23,53]. However, by the mid-1980s, as the predicted shortages did not occur, questions were raised and it was found that the actual supply was grossly underestimated [23]. Some of the underestimate has been explained by lack of consideration of wood available from outside forests (e.g. parks, roadsides), which were often not counted in supply estimates, but continue to deserve further attention in development of national estimates. By the 1990s, revisions to predictions of the fuelwood crisis became widely accepted, and programs to promote fuelwood supply were redirected [23].

Further examination of fuelwood supply and its contribution to deforestation paints a different picture than the f_{NRB} default values under the CDM. Conclusions developed from studies in several countries found that on a national level, fuelwood demand is unlikely to deplete forest resources or reduce forest cover, but localized scarcities do occur where there is an imbalance between demand and availability [23]. Additional studies examining the causes of tropical deforestation have found only weak evidence that fuelwood is a primary driver, and is instead an "occasional cause" in select regions [23,54]. While these results do not suggest that fuelwood does not contribute to deforestation, they do indicate a need to perhaps reexamine some of the assumptions underlying these methodologies, especially the current CDM default values.

3.3. Estimating CO_2 Emissions from Cookstoves: $Ef_{proj\_fossilfuel}$

Under the CDM methodology AMS II.G, the quantification of project emission reductions (see Section 3) relies on the factor $EF_{proj\_fossilfuel}$, representing the fossil fuel emission factor of "substitution fuels likely to be used by similar users" [25]. The use of fossil fuel emission factors for baseline fuels represents something of a clever workaround to the restriction that the CDM cannot cover avoided deforestation. Nonetheless, it has been roundly criticized. Johnson et al. [34] say it has "no scientific basis, given that wood emits approximately double the CO_2 per unit fuel energy compared to LPG or kerosene thus halving possible offsets from non-renewable harvesting of fuel". Other studies and technical experts interviewed agree that using fossil fuel emission factors has the effect of reducing the CERs claimed, by around 30%. This is down from a 40% reduction in earlier methodology versions [55]. Emission factors for several fossil fuels are compared with wood in Table 3. The CDM methodology AMS II.G. suggests the use of a weighted average value of 81.6, representing a mix of 50% coal, 25% kerosene, and 25% LPG.

The reason for using fossil fuel emission factors for cookstove projects is that the Marrakesh Accord allows for non-afforestation project activities to consider a reduction in carbon stocks as emissions, but not to get credits from any increase in carbon stocks [18]. Still, it is an imperfect workaround. For charcoal production, the simplification is stretched beyond reality. As shown in project design documents (e.g. [31]), there is a precedent for calculating wood use by charcoal stoves by multiplying the charcoal volume by six, following the 1996 IPCC accounting guidelines to estimate total biomass consumed (Reference Manual, p. 1.42, [56]). Then baseline emissions are estimated by applying the projected fossil fuel use emissions factor, which in effect assumes that the project displaces fossil fuel use for charcoal production. Despite concerns over the use of fossil fuel emission factors, project developers interviewed recognized that changing this approach in the CDM methodology will be a significant challenge. Revisiting the biomass emissions factor would require an endorsement by the CMP, which would involve a lengthy review period with uncertain outcomes.

4. Estimating other Emissions and Climate Impacts

Methodologies vary in the types of cookstove emissions considered eligible for crediting. While all methodologies credit CO_2 emissions, only a subset include CH_4 and N_2O and none include short-lived climate forcers, such as black and brown carbon. Emission reductions of these other gases and short-lived aerosols from improved cookstove efficiency could reduce not only the radiative forcing and climate warming impact, but also provide significant co-benefits for health [57].

Under the AMS II.G and I.E methodologies, stove projects can only receive credit for reducing CO_2 emissions. Revising this approach has been considered by the CDM SSC WG, but since these methodologies require projects to assume the use of fossil fuel, it becomes inconsistent to include other emissions from future wood combustion. Under the Gold Standard methodology, however, projects may also get credit for reductions in methane and nitrous oxide (CH_4 and N_2O) emissions [19]. Using the Gold Standard approach, the combined effect of the additional accounting of CH_4 and N_2O emissions from biomass combustion, plus the use of real conditions for the baseline (instead of fossil fuel values as in AMS II.G) can double the estimated emission reductions for stove projects [55]. The exclusion of CH_4 and N_2O emissions accounting, beside potentially under-crediting emission reductions, could also result in incorrect judgements about the relative benefits of different stoves [42]. Project developers interviewed noted that the current effort to develop a modification to the CDM AMS II.G methodology through the American Carbon Registry will allow for the inclusion of CH_4 and N_2O emissions in addition to CO_2.

Table 3. Comparison of fuel emission factors.

Fuel	Fossil fuel emission factor (tCO_2/TJ)	Source(s)
Wood	121	Johnson et al. [34]
Coal	96	CDM methodology AMS II.G.
Kerosene	71.5	CDM methodology AMS II.G. Johnson et al. [34] IPCC default
Liquefied petroleum gas (LPG)	63.0	CDM methodology AMS II.G. Johnson et al. [34] IPCC default
Weighted average (50% coal, 25% kerosene, 25% LPG)	81.6	CDM methodology AMS II.G.

Emissions factors used in the methodologies rely on IPCC default factors, which express emissions as a function of the energy content of fuels consumed. Researchers and market actors recommend that emissions factors be refined to incorporate in-field emissions data based on the mass rather than the energy content of fuel consumed. Berkeley Air has worked extensively in this area, with support from the U.S. Agency for International Development and the U.S. Environmental Protection Agency, conducting in-field emissions monitoring CO_2, carbon monoxide (CO), particulate matter (PM), black carbon, as well as through the development of emissions monitors for PM and CO. There is still more work to be done in this area, however, and data collection is costly [58].

Cookstove emissions also include short-lived aerosols that have a large climate impact but are not yet considered by methodologies. Black carbon, which results from the incomplete combustion of fossil fuels and biomass, has complex effects on climate. Although ground-level concentrations of black carbon are far lower than for CO_2, black carbon absorbs one million times more energy per unit mass than CO_2, On a global basis, the current instantaneous radiative forcing of black carbon could be close to half that of anthropogenic CO_2 [59]. However, this is only one of the ways that black carbon affects the climate. There remains a good deal of uncertainty about black carbon's climate impacts, as it also affects albedo (e.g., when deposited on white snow or ice), absorbs light and leads to faster melting, and also interacts with clouds, altering reflectivity and lifetime [49].

Solid biomass used for cooking and heating is estimated to contribute 25% of black carbon emissions globally [60]. As black carbon emissions from transport and industry are expected to decline due to planned interventions, the share of black carbon from traditional bioenergy use in developing country households in Asia and Africa is expected to make up close to half of all global black carbon emissions by 2030 [59].

Black carbon and other short-lived climate forcers (e.g., brown carbon [61], carbon monoxide and non-methane hydrocarbons) are known to contribute to warming, but have been excluded from climate agreements such as the Kyoto Protocol and offset schemes, in part due to their short and complicated life cycles and varied impacts [62]. The argument for using carbon finance to switch from traditional to improved cookstoves "would be even stronger were the non-Kyoto substances and their large short-term impacts considered in this comparison" [62]. Results from an improved cookstove project in Mexico suggest that excluding other greenhouse gases can result in underestimating emissions reductions by 64% [42].

Recent work suggests that of the options for reducing black carbon emissions, residential stove and fuel interventions offer the highest net benefits per cost [63]. While development of emission factors for black carbon, and an applicable conservative crediting approach, was noted by market actors interviewed as providing a potential real benefit for capturing this emissions source from projects, progress has been limited by the site-specific nature and the complexity of black carbon compared with other emission sources [64].

5. Conclusion

Carbon offset markets can provide a valuable means to support the further dissemination of improved cookstoves in developing countries. Offset markets can bring new sources of private-sector finance into projects and help to establish standards for monitoring and accountability, two recognized needs for cookstove projects. In addition, the methodologies developed for offset projects can also be used for Nationally Appropriate Mitigation Actions (NAMAs) and other forms of carbon finance; in particular those that involve payment for performance in reducing GHG emissions, to further expand implementation.

Nevertheless, this review suggests there remains considerable room for improvement in how offset methodologies account for the climate benefits of improved cookstoves. Our review of lessons learned and conversations with market actors and researchers has identified the following needs and potential directions for future research:

- Require accounting of uncertainty in estimates of emission reductions: Prior work has documented that uncertainty in the estimates of fuel usage, emission factors and fraction of non-renewable biomass (f_{NRB}) can be large [34], yet current methodologies do not require accounting for uncertainty. This could be addressed in methodologies by requiring that the IPCC recommendations for uncertainty from the Good Practice Guidance and Uncertainty Management in National GHG Inventories be applied to project emission reductions calculations.
- Develop additional default factors for biomass consumption from baseline stoves: Currently the Clean Development Mechanism (CDM) methodology does not provide adequate default baseline fuelwood consumption values. Development of additional default factors could reduce uncertainty and further standardize estimates of baseline emissions. However, in 2012, a CDM technical working group found the variability in existing data estimates made development of default values unfeasible. Further work will depend on the availability of new research to address existing data gaps.
- Track the application, and review the integrity, of the new CDM default factors for f_{NRB}: As discussed above, there is reason to believe that the current default factors, which imply that over 80% of all biomass use is non-renewable in the large majority of countries assessed, could overstate the fraction of non-renewable biomass in some project circumstances. Application of community and sub-national modelling assessments should be encouraged to validate and improve upon these values.
- Refine approaches to incorporate the use of data loggers in project monitoring: while it is generally assumed that new stoves replace old stoves for all cooking needs, observations suggest that this is not the case. Monitoring under the CDM currently requires that traditional stoves either be disposed of or continue to be monitored to determine ongoing usage. Ongoing monitoring of traditional stove use presents a challenge. Some have proposed using data loggers, to measure real fuel usage in households and gauge the new stoves' impact. However, further refinement is needed on how best to incorporate data loggers into monitoring plans and quantification of emission reductions in methodologies.
- Revisit the use of fossil fuel CO_2 emission factors as surrogates for biomass combustion: under the CDM methodology, CO_2 emissions factors for cookstoves are based on fossil fuel emissions, justified as the "substitution fuels likely to be used by similar users" [25]. This approach is largely a result of the constraints of the Marrakesh Accords that non-afforestation project activities cannot get credit for any increase in carbon stocks; however it remains an unsatisfactory work-around. This approach may result in a large under-crediting of cookstove projects and deserves further evaluation and review.
- Consider non-CO_2 greenhouse gas emissions: Under the CDM methodologies, methane and nitrous oxide emissions are not considered, as they are under the Gold Standard methodology. Omission of these gases may not only result in under-crediting of cookstove projects, limiting their implementation, but could also lead to incorrect judgements about the relative benefits of different stoves [42]. Despite challenges in estimation methods for these gases, further research is needed to consider conservative ways to incorporate these emissions into current methodologies.
- Develop approaches to incorporate black carbon: Black carbon can make up a large portion of the climate impact of cookstove use, and yet it is not currently considered by carbon market methodologies. The site-specific and complex nature of black carbon emissions' impact complicates their inclusion; new approaches will be needed that may differ radically from those currently used in project-based carbon accounting. The Climate and Clean Air Coalition, in which many countries and organizations participate, could provide a forum through which to pursue new methods.

Acknowledgements and Disclaimer

This study was made possible through financial support from the Swedish International Development Cooperation Agency (Sida). However, Sida was not involved in the design of the study and does not necessarily support the views expressed here, which are strictly the authors'.

We thank the market actors and technical experts we interviewed for sharing their valuable insights on lessons learned from implementing and evaluating improved cookstove projects. In particular, we thank the following individuals for providing their input: Robert Bailis (Associate Professor, Yale University), Neil Bellefeuille (Chief Executive Officer, The Paradigm Project), Simone Brant (Program Manager, Berkeley Air), Kai Carter (Impact Carbon), Gajanana Hedge and Julieta Nikova (Sustainable Development Mechanisms Methodologies Team, UNFCCC Secretariat), David Pennise (Technical Director, Berkeley Air), Dean Still (Executive Director, Aprovecho Research Center), Jimmy Tran (Director of Project Development, Impact Carbon), and Erik Wurster (CEO, UpEnergy).

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Appendix 1. List of Acronyms

ACR	American Carbon Registry
B_y	biomass fuel consumption
CCT	Controlled Cooking Test
CDM	Clean Development Mechanism
CDM SSC WG	CDM Small-Scale Working Group
CERs	Certified Emission Reductions
CH_4	methane
CMP	Conference of the Parties (to the Kyoto Protocol)
CO	carbon monoxide
CO_2e	carbon dioxide equivalent
$EF_{proj\_fossilfuel}$	emission factors for fuel combustion
EU ETS	European Union Emissions Trading System
f_{NRB}	fraction of non-renewable biomass
GHGs	greenhouse gases
GS	Gold Standard
Gt CO_2	gigaton of carbon dioxide
IPCC	Intergovernmental Panel on Climate Change
KPT	Kitchen Performance Test
LDCs	Least Developed Countries
MAI	mean annual increment
NAMAs	Nationally Appropriate Mitigation Actions
NCV	net calorific value
N_2O	nitrous oxide
PDDs	project design documents
PM	particulate matter
PoAs	Program of Activities
SIDS	Small Island Developing States
UNFCCC	United Nations Framework Convention on Climate Change
VCS	Verified Carbon Standard
VERs	Verified Emission Reductions
WBT	Water Boiling Test
WISDOM	Woodfuel Integrated Supply/Demand Overview Mapping

Challenges in Sustainability | 2013 | Volume 1 | Issue 2 | Pages 72–79
DOI: 10.12924/cis2013.01020072

Review

Building Disaster Resilience: Steps Toward Sustainability

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Submitted: 2 September 2013| In revised form: 5 December 2013| Accepted: 18 December 2013 | Published: 29 January 2014

Abstract: Disaster losses continue to escalate globally and in many regions human losses (death, injury, permanent displacement) often exceed the economic toll. Current disaster policies are reactive with a short-term focus—respond and rebuild as quickly as possible and in the same way after the event. Such policies ignore the longer-term approach of building disaster-resilient communities, in which investments made now show financial and social returns later by reducing the impact of disasters. This article provides a vision for resilient nations in 2030 based on three recent policy reports. It highlights the necessary steps towards achieving sustainability using the lens of disaster resilience as the pathway towards strengthening communities' ability to prepare and plan for, absorb, respond to, and recover from present and future disasters.

Keywords: disaster resilience; Hyogo Framework for Action; risk management; sustainable development

1. Introduction

Some hazards, such as hurricanes, tornados, wildfires, and avalanches occur during specific time periods of the year, while others, like earthquakes do not. Some hazards are place-specific—the tectonically active Pacific Rim, coastal environments—while others, especially severe storms, are ubiquitous and found almost everywhere. Human-made hazards can occur anywhere, as can health-related hazards such as pandemics. The result: no single person or place is totally immune from hazards or their adverse impacts. As more and more people move to hazardous environments such as coasts and floodplains, the potential for increasing disaster risk intensifies as more people and infrastructure are placed in harm's way. In the United States, migration to the coasts, along with an increasing and aging population and public infrastructure that is equally old and beyond its design limit, set the stage for greater impacts from hazards. This scene is replicated in many other places such as Japan, and EU countries. In other world regions rapid urbanization and growth of mega-cities where more than half of the world's population now lives and where local wealth is most concentrated are amplifying disaster risk as well.

We need not look further back than the last couple of years to see the escalating losses associated with disasters. The year 2012 is considered a moderate year for losses, with global economic losses totaling US$170 billion, slightly above the ten-year average, although fatalities were lower than normal [1]. Globally, there is a worrisome trend in increasing weather-related losses, a trend that is clear even when the raw data are normalized by inflation and GDP [2]. When using other normalization proxies (such as inflation, GNI per capita, insurance penetration, or building stock development) the increase remains, averaging $750 million per year in annual losses [3]. In the U.S., the number of individual events producing economic losses exceeding a billion dollars has increased. In 2010, for example, there were 4 billion dollar events; in 2011 there were 14; and in 2012, there were 11 [4]. Trends in human losses (people killed, injured, displaced, or affected) during the last decade fluctuate and illustrate the effect of a single catastrophic event—2004 Indian Ocean tsunami, 2008's Cyclone Nargis, and the 2010 Haiti earthquake. Without these large events, there is an apparent decreasing trend in disaster fatalities, with 2012 recording one of the lowest numbers of fatalities from disasters in more than a decade [5].

Disaster losses are occurring at a time of slower economic growth (regionally and globally), reductions in coastal and riverine defenses that protect communities from flooding and storm surge, and the increasing impacts of climate change from local to regional to global levels. The impacts of disasters are greatest in already impoverished communities, regions, or countries and such impacts will increase in the future. Communities and the nations that contain them cannot continue to shoulder the financial or social burdens of these losses each year—they are not sustainable in either the short or longer term [6]. Communities and nations face difficult choices (fiscal, social, environmental) about their existing vulnerabilities, present and future security, and quality-of-life.

This paper summarizes the actions needed to enhance disaster resilience based on recent reports by the United Nations [7], the UK Government Office for Science [8], and the U.S. National Research Council [9]. It argues that disaster resilience is the pathway for linking disaster risk management and the long-term sustainability of communities, through a series of action-oriented steps that involve combinations of top-down (internationally and nationally-driven) and bottom-up (community-based) strategies. The idea is certainly not new within the academic literature [10, 11], with some researchers re-conceptualizing resilience as "bouncing forward not bouncing back" to some previous condition [12]. However, within the policy realm linking disaster risk, resilience, and sustainability, this notion is relatively new and represents a shift in thinking regarding disaster risk management.

2. Linking Disaster Risk Management and Sustainable Communities

Linking disaster risk management and sustainable development begins with understanding the commonalities in each construct and their geographic and temporal manifestations. Disaster risk management is the "process that weighs policies, plans, and actions for reducing the impact of disasters on people, property, and the environment" ([9], p. 28). It includes the identification of hazards and exposures, assessments of the risk in terms of potential losses, the development of capacities and implementation of strategies to prevent, reduce, mitigate, recover, or prepare for disasters, and evaluation of the effectiveness of these policies and programs.

Sustainability is the potential to maintain the long term well-being of communities based on social, economic, and environmental requirements of present and future generations. It stresses the interdependencies of environmental protection, human needs, and societal well-being [13,14], acknowledging the primary goal of improving the human condition without harming the environment. In the context of hazards and disasters, "sustainability means that a locality can tolerate—and overcome—damage, diminished productivity, and reduced quality of life from an extreme event without significant outside assistance" ([15], p. 4). How and where development should proceed in communities if they are to become sustainable begins with a set of principles that foster sustainable mitigation. These principles maintain and enhance environmental quality and quality of life, foster local resilience, recognize that vibrant communities are essential, ensure intra- and intergenerational equity, and adopt local consensus building.

Fundamentally, resilience is a capacity measure that can be viewed as sector-focused, systems-based, or, applied more broadly to a community, defined as systems of systems where the various components—environment, infrastructure, social, economic, institutional and so forth—are integrated and mutually supportive. There is rich and growing body of literature on resilience, ranging from definitional clarifications to conceptual frameworks to applications of the resilience concept in specific environments such as cities or to topical areas such as climate change or sustainability [16-23]. Despite such robust research there is no universal agreement on the specific definition of disaster resilience, yet there is some consensus on its broad parameters, specifically the capacity to recover from or improve functions after a hazard event. For example, an US NRC report defined resilience as "the ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse eve-nts" ([9], p. 1). This is similar to the UK Foresight report that defines resilience as "the ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions" ([8], p. 17).

What links disaster risk management to sustainability is resilience (Figure 1). The present focus on the disaster cycle especially response and recovery must be targeted more broadly on strategies to manage disaster risk in both the long and short terms [24,25]. There are many different paths for achieving long-term viability and self-sufficiency of communities from a hazards and disaster perspective. Such pathways are designed to enhance resilience by instituting a culture of resilience through managing residual disaster risk, reducing vulnerability, having strong leadership from government and civil society, implementing institutional reform of policies and practices at all levels, building local capacity including peer-to-peer learning, developing and deploying tools and metrics for monitoring progress, and reducing gaps in our scientific information, data, and observation systems. Disasters retard development gains through the destruction of livelihoods and community assets, increase poverty, and stimulate repopulation in high-risk (and largely unsustainable) damaged areas. Disasters, therefore, become perverse incentives for communities and nations to divert from normal development processes in order to facilitate response and recovery. From a policy perspective then, thinking about and planning for resilience as part of disaster risk management and sustainable development strategies and programs becomes an important element in the process of achieving sustainable and thus disaster resilient communities.

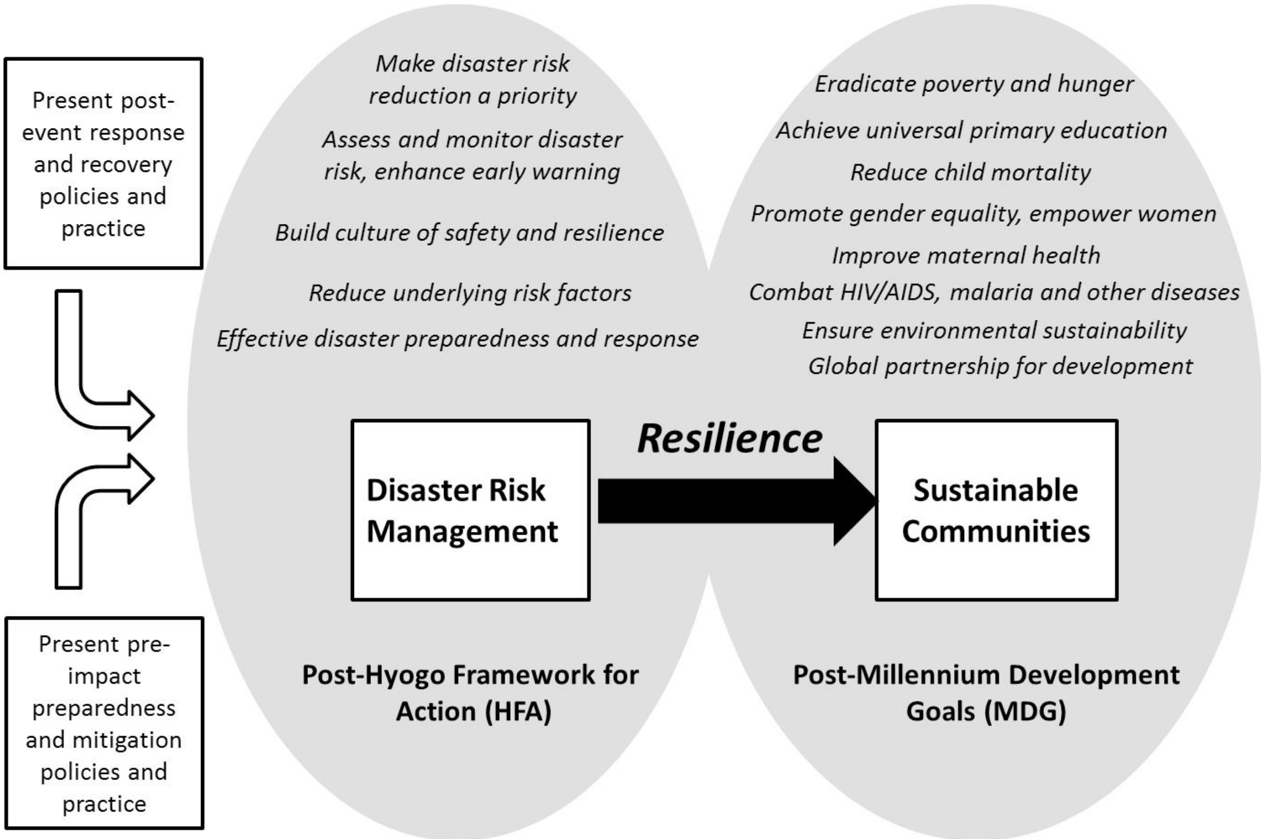

Figure 1. The path to a disaster resilient future.

3. Why is Resilience so Important Now?

Extreme natural events (either unprecedented magnitudes or intensities of natural hazards, or the unprecedented consequences of more routine hazards), may become increasingly normal or routine under changing climatic conditions or changes in economic circumstances and social conditions [26]. Coupled with the increasing interdependence and interconnectedness of society, hazards, while local in origin, can cascade into global events with national and international policy implications [27,28].

Low probability, high consequence events including highly improbable ones take on more policy interest as these events become more probable [29-31]. From a policy perspective, such events pose significant management challenges. The complexity, interconnectedness, uncertainty, and unforeseen consequences associated with these types of events make them difficult to solve. Incomplete or contradictory information, changing conditions and requirements that are not easily recognized by decision makers, and the complex interdependencies of the individual facets of the problem themselves raise a set of questions as to how one can encourage investments in risk reducing measures prior to these unthinkable or unpredictable events [32,33]. These so-called wicked problems are so interconnected that in solving one aspect of the issue, another problem one might ensue. For example, in partial response to the Fukushima Dai'ichi nuclear meltdown, Germany announced the closure of all of its nuclear facilities by 2020. The closure of nuclear power plants producing electricity raises a wicked problem for nations who are struggling to provide safe energy and reduce greenhouse gas emissions that contribute to climate change [34-36]. What is the alternative? What risks are involved in that choice? Will the nation be better or worse off? Disaster risk cannot be completely eliminated as there will always be some residual risk that requires management. This premise underscores that a proactive approach to risk management and improving disaster resilience is the only policy and the pragmatic option if we are to reduce the impacts of disaster losses in the long run.

Globalization and environmental change are normally studied independently, but it is the interaction of these processes that creates double exposures which in turn explain the uneven outcomes of disaster impacts [37]. These impacts are scale-dependent, ranging from the local community to the global, necessitating different governance structures and management regimes at all geographic scales—local, regional, national, international—and units of analysis ranging from the individual to the state [38]. For example, the widening gap in income equality between and within nations reduces local and national capacities to prepare for and respond to disasters by lowering social protection options. The eradication of poverty is perhaps the key to achieving resilience and more sustainable development along with socially inclusive productive and effective governance [39]. Urbanization is escalating worldwide, leading to decreasing resilience in world cities. In 2010, 52% of the world's 6.9 billion inhabitants lived in urban areas, mostly in the less developed world. By 2030, more than 60% of the world's population (projected to be 8.3 billion) will live in urban areas, primarily in Asia [8]. Many of the major cities are located along the coasts, on inland waterways, or in active seismic regions—areas susceptible to cyclones, flooding, and earthquakes. With the increasing exposure and likely impacts associated with climate change, globally more people are in harm's way than ever before. Unless cities and nations become more resilient, the disaster toll in terms of human lives and economic losses will escalate, potentially reversing the downward trend in fatalities over the last decade.

Finally, the Hyogo Framework for Action (HFA) is nearing the end of its 10-year plan. Global consultations (termed HFA2) are already underway to develop a post-2015 disaster risk framework that includes not only disaster risk reduction, but disaster resilience as well. These efforts will be presented at the World Conference for Disaster Risk Reduction in Japan in early 2015. Simultaneously, the Millennium Development Goals will also be completed at the end of 2015 and consultations on a post-2015 Development Agenda also are underway. One of the universal goals, ending poverty, has a specific disaster risk reduction target: building resilience and reducing deaths from natural disasters [7]. How the HFA2 goals for risk reduction and resilience are reflected in the post-2015 Sustainable Development Goals is uncertain. The incorporation of resilience into the preparatory meetings on the Post-Hyogo Framework for Action (HFA2) and the Sustainable Development Goals illustrates how important the concept of resilience is to both disaster risk management and sustainable development. This linkage enables movement from short-term thinking and strategies to longer-term, more sustainable practices that not only empower communities, but enable them to improve the human condition and reduce disaster risk.

4. Building Resilience

In reviewing the key findings of the three reports [7-9] a general scientific consensus emerges on the need for disaster risk management and improving resilience at all levels of governance. The main findings are summarized in Table 1 and briefly described below. First, reducing risk requires a process of risk identification, development of a strategy to deal with risk, and keeping the strategy flexible and current [9,40]. Risk management also necessitates multiple collaborators and stakeholders and a mix of structural or construction-related (e.g. levees, retrofitting buildings) and non-structural (land use, insurance) tools to ensure resilient infrastructure.

Second, there is a need to demonstrate that investments in resilience will yield measureable short/long-term benefits, but existing disaster loss and damage data need improvements in order to do so. For example, there is no consistent standard for measuring losses or which losses should be counted (e.g. deaths, property, decline in nature's services, or cultural assets in the community) [41-43].

Third, resilience has many different facets (economic, infrastructure, environmental, social, institutional, organizational, psychosocial) and objects of study (individuals, buildings, sectors, systems, communities, cities) [44]. While some national and international efforts are underway to measure community resilience [45-47], at present these efforts are not consistent with one another and often do not agree on what needs to be measured. Some important elements include critical infrastructure performance after disasters, social factors that influence the capacity to recover, the ability of structures to withstand the impact from disasters as related directly to building codes and their enforcement, the ability of businesses and markets to recover, and caring for special needs populations in times of crises.

Fourth, communities vary in their size, composition, and the range of hazards they are exposed to. A one-size-fits-all strategy for enhancing resilience does not consider the uniqueness and complexities of communities' physical and social structures. Instead, efforts should be directed towards building strong local capacity so that community members are engaged in disaster policy and practice, help communicate risk, adopt risk reduction measures, and plan for the worst, but strive for the best when a disaster hits their community [48]. Finally, many communities and nations do not have an overall vision or coordinating strategy for disaster resilience. A need exists for strong and complementary governance from local, state, and federal policies so they don't work at cross-purposes [49]. Policies at all levels also need to take longer-term views rather than address short-term political expediencies [50].

There are a number of enabling conditions that can help foster disaster resilience at local to national levels. First and foremost, there must be leadership and the political will to embark on a different path for managing disaster risk. Without such leadership, resilience actions will be short-lived and will not achieve the longer-term desired benefits. Another enabling condition is governmental engagement in risk reduction, one of the leading pillars of the Hyogo Framework for Action (see Figure 1). Such engagement should occur at all levels (from local to national) so that the combined governmental efforts are complimentary and working toward a common goal, rather than working at cross-purposes. Similarly, risk reduction should entail cross-sector linkages, involving private interests and civil society. Communities must be willing (and able) to engage in peer to peer learning and to take good ideas from one place and adapt them to their own circumstances. Lastly, resilience must be integrated into overall planning efforts that address infrastructure deficits, improve livelihoods and economic opportunities, and reduce social inequalities, ideals embodied in the Millennium Development Goals.

Table 1. Actions to increase disaster resilience.

- Manage risks with flexible strategies and multiple tools
  - Integrate disaster risk management and planning into day-to-day activities
  - Encourage public-private cooperation in risk management
  - Use complimentary approaches and tools (structural, non-structural)
  - Develop an essential framework of codes, standards and guidelines that increase resilience of structures
  - Implement risk-based pricing of insurance
- Improve the accuracy and consistency of disaster data
  - Establish and improve a national/international databases on disaster-related information
  - Document disaster deaths, injuries, property loss, impacts on economic activity
  - Improve valuation of community assets including ecosystem services
  - Estimate future disaster losses for planning
  - Improve risk management information and integrated models of exposure and vulnerability metrics
- Measure resilience and chart progress toward achieving it
  - Establish a baseline of resilience for nation and communities
  - Create metrics for measuring progress and effectiveness of actions
  - Ensure robust analyses of the effectiveness of actions and programs to build resilience
- Build strong local capacity
  - Foster early engagement stakeholders and residents in the risk management process and collaborative problem solving
  - Create and financially support broad-based community resilience coalitions
  - Ensure local governments adhere to modern zoning laws, and adopt and enforce building codes
  - Share experiences, learn from other communities, innovate
- Create an overall vision or coordinating strategy for disaster resilience
  - Incorporate resilience as a guiding principle in practice and programs at all government levels
  - Review resilience policy and programs and undertake self-assessments to ensure coordination of federal to local efforts
  - Develop and share guidance on resilience initiatives from global to local scales;
  - Incentivize private sector and non-governmental organizations to engage in resilience activities

Source: [7–9].

5. How Do We Get There?

Many different avenues are available for achieving the long-term viability and self-sufficiency of communities with respect to hazards and disasters. The pathway for achieving the vision of a resilient nation in 2030 for the United States, for example, begins with the aspiration to establish a culture of resilience through leadership from the federal government with a full and clear commitment to disaster resilience [9]. In order to achieve such a goal a number of steps would be needed; steps that are targeted to national and local governments, stakeholders, and citizens. First, in addition to this recognizable culture across the nation, there would be the knowledge and understanding that communities (and individuals) would be the first line of defense in enhancing resilience by taking responsibility for their actions in managing (or mismanaging) disaster risk. Second, leadership is an important component in fostering resilience, and there would be national leadership in all federal agencies and in Congress as well as local and state advocates championing the values of disaster resilience. Such leadership would insure that infrastructure systems are upgraded and redundant in order to lessen the impacts of disasters. It also would ensure a periodic review of federal, state, and local programs or policies to insure that resilience actions are supported not reduced. Third, community-led resilience efforts would receive federal, state, and regional investments and support. Reliance on underfunded and solely volunteer efforts would become the exception, not the rule. Fourth, to more fully manage risks, local zoning ordinances would be enacted and enforced, as would building codes and retrofit standards. Such enforcement would enhance disaster resilience at the local level as these ordinances and codes are under local jurisdictions, not state or federal control. Fifth, site specific risk information would be readily available at all scales and effectively communicated to relevant stakeholders from local to national levels. And finally, insurance premiums would become risk-based, so that individuals and communities with the highest risk would bear a greater share of the cost of risk premiums. This would enable post-disaster recovery to be funded primarily through private capital and insurance payouts rather than federal resources. More importantly, such actions would provide the financial mechanism to ensure that communities and individuals take responsibility for their risk decision making.

If these proactive steps were taken, we could see a reduction in the per capita federal cost of responding to disasters in the U.S. We would also see a decline in overall disaster losses because of these long-term investments in resilience.

Disaster resilience links disaster risk management and sustainable development, especially in the developing world. Unlike the national example, the global path requires some transformative shifts in the business-as-usual model, one that is more planet-sensitive, people-centric, and harmonized with local-national approaches such as those outlined above for the U.S. The five pillars of the global transformation include: to leave no one behind; put sustainable development at the core; transform economies for jobs and inclusive growth; build peace and transparent and accountable institutions; and forge new global partnerships [51]. If such a transformative shift takes place, by 2030 the world would see increased resilience and improved quality of life. There would be fewer people in extreme poverty, more children living beyond the age of five, less mortality from childbirth, more sustainable use of natural resources, improvements in education and employment, and more participatory governance and accountability at all levels (local to regional to national). More significantly, such actions would result in 220 million fewer people suffering the crippling effects of disasters ([51], p. 19).

6. Conclusions

The present focus on the disaster cycle must be targeted more broadly on strategies to build resilience as the transition to sustainability. The mechanisms involve managing disaster risk, undertaking institutional reform of policies and practices at all governance levels, building local capacity, development and deployment of tools and metrics for monitoring progress, and investment in the reduction of gaps in our scientific information, data, and observation systems. As the World Bank recently stated, "the international community should lead by example by further promoting approaches that progressively link climate and disaster resilience to broader development paths, and funding them appropriately" ([52], p. 9). The most significant challenges to achieving the transformation are institutional, political will, and leadership and these challenges exist at global to local scales.

Enhancing disaster resilience requires the coordinated efforts of individuals, families, communities, the private sector, and government at all levels. The path to disaster resilience requires a blending of top-down (global to local) and bottom-up (local to global) approaches as no single person, agency, or institution has all the responsibility for improving resilience; must be a collective effort with shared responsibilities. Achieving disaster resilience will not be cheap or easy, but it is becoming both an economic necessity and a moral imperative. We must have the political will to move from the present focus on short-term disaster response to a longer-term vision of a more sustainable future that embodies the basic principles of resilience as outlined here. When we have achieved some success in enhancing our collective resilience to disasters, we will secure the future livelihoods and prosperity for our children's future.

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DOI: 10.12924/cis2013.01020080

Challenges in Sustainability

Opinion

Publishing Sustainability Research Visually: A Film about the Opportunities and Challenges of a Rural Entrepreneurship Initiative in Kenya

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Submitted: 17 January 2014 | Accepted: 18 February 2014 | Published: 27 February 2014

Keywords: entrepreneurship; film; improved cookstoves; innovation diffusion; Kenya; poverty; rooftop water harvesting systems; sustainability

1. Knowledge Dissemination and Film

We have witnessed a large increase in the number of publications on sustainability challenges over the past decade. One important characteristic of the research is with the wide variety of actors that can make use of the results. Sustainability knowledge is often not only relevant for those in academia or policy-making circles, but it can also be useful for decision-makers in a diversity of societal facets and sectors. It is therefore essential that the sustainability research community have access to a diversity of knowledge dissemination outlets, including those that extend beyond the traditional, and often inaccessible, academic publishing realms. One positive development over the past decade in sustainability research reaching broader audiences has been the proliferation of open access publication outlets. The alternative has provided greater access to scientific articles to almost anyone with an Internet connection. But, is this medium of knowledge dissemination sufficient? Are there additional channels that sustainability researchers can use to broadcast knowledge to even broader user groups?

Another dissemination medium that has developed rapidly, especially since the advent of commercial websites such as *Youtube* and *Vimeo*, is film. These platforms have created places for individuals to share information. Despite the rapid growth and great potential of this medium, there are, however, a variety of challenges that must be overcome in using film as an effective form of knowledge transmission in sustainability research. For example, filmmaking skills—such as effectively combining the multiple formats of film clips, photos, narration, and sound—must be developed by researchers in a manner that the film conveys a clear and concise message, is academically rigorous, and, most importantly, holds viewer attention. Furthermore, academic publishing outlets must develop the systems and procedures to meet the demands of film (e.g., DOI numbering, peer review processes, managing large file sizes).

Video 1: Film on entrepreneurship initiative in Kenya.

2. Innovation Diffusion in Kenya

The 18-minute film presented here (Video 1) represents a first small step in uniting open access publishing with a dissemination medium other than the conventional academic article. The film is a part of outreach efforts at the Centre for Sustainability Studies at Lund University to explore and encourage different forms of knowledge to action, especially to those with an interest in poverty alleviation and sustainability in the global South. The film presents the accomplishments and challenges of a rural sustainable development initiative in rural Nyanza Province, Kenya. It focuses on the sale and financing of simple technologies through an entrepreneur. The technologies introduced are improved cook stoves and rooftop water harvesting and storage systems. The film describes the approach, the technologies, and early achievements of the initiative. It then concentrates on the major challenges encountered by the entrepreneur in trying to sustain the initiative throughout the first years of operation, with a special concentration on maintaining the capital to sell additional innovations. The film furthermore addresses solutions to this challenge including the establishment of detailed written contracts, a modest late fee for late payments, a witness to the purchase contract and mobile telephone money transfer options.

The use of film as knowledge dissemination in sustainability research will become more ubiquitous as the obstacles are overcome. There are currently several developments underway including the addition of filmmaking training into educational programs in sustainability, and the creation of new and novel forums for spreading knowledge on sustainability via film. We welcome the developments.

Challenges in Sustainability | 2013 | Volume 1 | Issue 2 | Pages 82–93
DOI: 10.12924/cis2013.01020082

Review

Knowledge Governance for Sustainable Development: A Review

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Submitted: 5 September 2013 | In revised form: 7 January 2014 | Accepted: 26 February 2014 | Published: 12 March 2014

Abstract: Sustainable development is a knowledge intensive process, but plagued by persistent concerns over our apparent inability to connect what we know with more sustainable practices and outcomes. While considerable attention has been given to ways we may better understand and enhance the knowledge-based processes that support the governance of social-ecological systems, relatively few have examined the governance of knowledge itself. The institutions—rules and norms—that govern knowledge may shed light on the persistence of 'gaps' between knowledge and action. In this review I seek to answer the question: can interdisciplinary knowledge governance literature contribute to understanding and analysing the institutional knowledge-based dimensions of sustainable development? I present and analyse the concept of knowledge governance as it is emerging in a range of disciplines and practice areas, including private sector management literature and public regulation theory and practice. I then integrate the findings from this review into a model of sustainable development proposed by Nilsson et al. [1]. I show that knowledge governance (as a scale above knowledge management) can inform Nilsson et al.'s three "nested" dimensions of sustainability: human wellbeing (through access to knowledge and freedom to exercise informed choice); resource-base management (though enhancing regulation and innovation and transitions from exclusive to inclusive knowledge systems); and global public goods (by balancing public and private interests and fostering global innovation systems). This review concludes by presenting a framework that places sustainable development in the context of broader socio-political struggles towards more open, inclusive knowledge systems.

Keywords: global public goods; innovation; knowledge governance; knowledge systems; sustainable development

1. Introduction

Public debates and political struggles over how to achieve sustainability, from climate change and biodiversity conservation to genetically modified organisms and food security, have been characterised by clashes and controversies over knowledge [2,3]—what do we need to know to meet sustainability challenges? Who should know it? Where should that knowledge come from? Who has authority or should be believed? How can different forms of knowledge be harnessed more effectively for action towards sustainability? Yet despite substantial work in these areas [3–10] there remains a view that efforts to improve the application of knowledge to inform sustainable development have fallen short of the urgent and compelling need. This is particularly so in relation to science; for example, a United Nations Environment Program Foresight report released in 2012 ranked "Reconnecting Science and Policy" as the fourth highest priority of 21 top challenges for sustainability in the 21st century. They stated that "…our society needs strategies and policies that are underpinned by a strong science and evidence base. But many believe the linkage between the policy and science communities is inadequate or even deteriorating, and that this 'broken bridge' is hindering the development of solutions to global environmental change. This problem requires a new look at the way science is organized and how the science-policy interface can be improved" [11]. Similarly, a report by the International Council for Science wrote "there appears to be a serious disconnect between scientific knowledge and the way that policy is formulated, leading to calls for improvements in the science-policy interface" [12]. A recent review of the usability of climate science for policy, including processes and techniques for enhancing the role of scientific knowledge in decision-making, concluded that: "in spite of these efforts to rethink and restructure science production, current approaches have not been able to surmount the usability gap" [9]. Beyond the science domain, arguments for more fully incorporating traditional ecological and indigenous knowledge into sustainability-related decision-making have long standing [13,14] with arguably increasing relevance in the context of global environmental change [15]. Other authors have highlighted the need for a range of knowledges to be brought together to address complex sustainability challenges, including contributions from local stakeholders (for a review, see Reed [16]), and dynamic and 'polycentric' governance arrangements to support adaptive management of "socio-ecological systems" [17,18]. Yet the difficulties of operationalising effective participation and adaptive governance arrangements have also been noted, suggesting that knowledge-oriented, learning-based approaches face substantial challenges in practice [16,19,20]. Taken together, the overall picture is that better understanding and enhancing the role of knowledge in sustainable development decision-making is widely held to be important, but there is a need for fresh insights and new ideas to 'bridge the gaps' between knowledge and action [21].

In this article I review the contribution one specific concept, "knowledge governance", may make to this broader task of understanding and enhancing the role of knowledge in sustainability decision-making. The origins of this review came about from a sustainability science project that ran in 2004–2006, titled "Knowledge systems for sustainable development". This project was made up of 9 case studies from around the world, where my colleagues and I sought to develop a systemic, actor-based understanding of knowledge processes in sustainable development projects [5,22–27]. While we developed a range of theoretical and practical insights from these projects, it became clear that the 'knowledge systems' we were identifying and describing emerged from complex governance arrangements that either supported or undermined efforts to build knowledge processes that could effectively support transitions towards more sustainable practices [23]. In other words, while we could describe the knowledge systems of our case studies, it was only by looking at the governance of these knowledge systems that we could start to explain how they actually came about or why they worked in the ways that they did. There seemed to be a middle layer, in between project-based knowledge management recommendations for improving communication and learning [28] or organisational recommendations regarding the importance of boundary organisations [27]; and analyses that address broader social, cultural and political aspects of knowledge [6,29], that was relatively un-developed. This middle layer was concerned with the institutional 'rules of the game' [30] that shaped the possibilities and choices available to decision-makers at organisational and project scales. Within that project, we had limited scope to develop these ideas further. In the intervening years, however, the term "knowledge governance" has emerged in a range of contexts and academic literatures to address this institutional layer—but not, by and large, in sustainable development (although other similar concepts have been used, which I will discuss shortly). Perhaps concepts that are gaining traction outside the sustainability domain can help to shed light on the persistence of the knowledge-action gaps identified earlier.

In this review I aim to see whether work conducted under the auspices of the term knowledge governance can offer new insights into the institutional and organisational challenges of sustainability, with regard to strengthening relationships between knowledge and action. I seek to answer the question: can interdisciplinary literature on knowledge governance contribute to understanding and analysing the institutional knowledge-based dimensions of sustainable development? I will first outline what is meant by knowledge governance, and how it relates to other knowledge-based concepts that have currency in sustainable development literature. I will then present a model of sustainability that highlights the foundational role of knowledge as proposed by Nilsson et al. [1], as a framework for analysing the literature. I will then review literature that discusses and develops the concept of knowledge governance in relation to private sector management and public sector regulation and legal frameworks. From this review I will return to Nilsson et al.'s model and suggest ways in which the knowledge governance literature may contribute to understanding and analysing the relationships between governance and knowledge for sustainable development.

2. What is Knowledge Governance?

Knowledge and governance are both contested terms with various definitions. Here, following our original project, I define knowledge simply as justifiable belief (where different forms of knowledge reflect different justifications) [8], and governance as a "system of formal and informal rules, rule-making systems, and actor-networks at all levels of human society (from local to global) that are set up to steer societies…" [31]. The essential proposition of knowledge governance is that the ways we conduct or engage in knowledge processes (such as creating, sharing, accessing, and using) are subject to formal and informal rules and conventions that shape our decisions and actions, and that these can be manipulated towards defined goals [32].

The different disciplinary contexts in which the specific concept of knowledge governance has been developed offer various definitions or interpretations of this broad idea. In the context of organisational economics, Foss [33] defines his "knowledge governance approach" as seeking to match knowledge transactions (or processes) with governance mechanisms, with a view to maximising economic efficiency. In relation to public problem-solving, Gerritsen ([34] p. 605) defines knowledge governance as "…the intentional achievement of societal and policy change through the purposeful production and dissemination of knowledge." Similarly, Burlamaqui describes knowledge governance as an approach that seeks "…to understand the interaction among knowledge production, appropriation and diffusion and, from a public policy/public interest point of view, to open up the space for a set of rules, regulatory redesign and institutional coordination which would favor the commitment to distribute (disseminate) over the right to exclude" ([35] pp. 4–5). These definitions point to two distinct sets of concerns that sit rather uncomfortably under the banner of "knowledge governance"—from the economic view, a means to improving efficiency and maximising return through understanding, designing and deploying knowledge governance mechanisms and tools; and from the public policy point of view, as a base for re-conceptualising the public interest and promoting societal transformations.

The implications and limitations of these perspectives will be examined in the next sections. For now, however, there are two key points to be made. First, importantly for the purposes of this review, knowledge governance relates to the 'institutional layer' mentioned earlier. It is broader in scope than knowledge management [32], which sits within the domain of projects and organisations, and is concerned with the institutional structures, rules and norms that enable or constrain knowledge management decisions. As Gerritson et al. ([34] p. 605) have written, "whereas knowledge management focuses on the management of the specific processes of knowledge production, like making knowledge questions explicit, organizing funding or sharing knowledge in workshops, knowledge governance is about engaging actors in innovative ways of solving societal issues". An illustration of the distinction is the often-heard tension between researchers understanding the importance of collaborative research agenda-setting with communities and co-production of knowledge (a way of organising and managing knowledge processes); but sitting within academic institutions that reward disciplinary focus and publication in academic journals (institutional rules and norms that devalue and divert effort from collaboration and co-production) (see, for example, Wiek et al. [36]). Knowledge governance as conceptualised here is concerned primarily with the broader scale of institutional rules and norms. Second, knowledge governance is regarded here as both a noun and a verb. As a noun, it is a description of existing phenomena, seeking to shine an analytical spotlight on the range of governance structures that already shape our knowledge processes in relation to sustainability, but are often obscured or subsumed by more tangible concerns. As a verb, knowledge governance is a suite of actions that may re-design or re-formulate these processes, towards sustainability-related goals.

Knowledge governance as a specific concept has not be widely used in sustainability-related domains, but has strong resonance with a number of areas such as post-normal science [37], sustainability science [10,4] Mode-2 knowledge production [38,39], adaptive governance [18,20] and social-ecological systems analysis [17]. Each of these areas emphasises the importance of collaborative knowledge construction for addressing complex problems, the crucial role of reflexivity and learning in the face of uncertainty, and the need for transdisciplinary, problem-focused knowledge strategies. The origins of this work, as outlined in the introduction, came from a study that was situated in the domain of sustainability science. A central concern of sustainability science has been to overcome the perceived 'gap' between knowledge and action [4]. The apparent intractability of shifting knowledge-based processes to models and practices that are better suited to tackling complex sustainability problems [9,12,40] is the area this review is intending to inform. The key point here is that this review focuses solely on the governance of knowledge processes, not on the role of knowledge in the governance of other issues related to sustainability (such as water, forests, energy etc). By drawing on literatures outside the more common sustainability parameters, I hope to complement the work that addresses knowledge processes related to sustainability science.

3. Sustainable Development: Knowledge Foundations

The potential connection between knowledge governance and sustainability can be framed in many ways. There are many definitions and constructs of sustainable development that have emerged since the popularisation of the term in 1987, and it is not possible to outline them here (but see, for example, Hopwood et al. [41]). In this review I draw on a model of sustainability proposed by Nilsson et al. [1] that was presented as a framework for sustainable development goals. It is particularly well suited to the purposes of this review as it specifically places both knowledge and governance as foundations for sustainable development. In the 'layer cake' diagram developed by Nilsson et al. (see Figure 1), they present three nested "tiers" of the sustainability agenda—human wellbeing, resource base management, and global public goods—that represent the ultimate goals of sustainable development. These tiers are applied across multiple "enabling goals", of which capacity and knowledge form the base layer, and institutions and governance form the layer above (see Figure 1). Analysis can then be conducted for a range of sectors ("slices"), relating each of the three nested tiers, across all four layers, in relation to the specific sector (in their paper they illustrate with the energy sector).

I will use this framework to analyse the knowledge governance literature presented in the next sections. Specifically, I will draw out whether and how the perspectives covered offer insights relevant to the tiers of human well-being, resource-base management; and global public goods. Nilsson et al.'s conceptualisation offers a clear role for analysing the governance dimensions of capacity and knowledge—essentially, the interplay between the two base layers, indicated by the dashed line in Figure 1. I do not argue that knowledge governance is the only resource needed for such a task—a full understanding of the capacity and knowledge dimensions of sustainable development and their relations to governance will require a broader scope than this. It is, however, a useful way to structure the following review that makes a ready connection to a relevant sustainability framework.

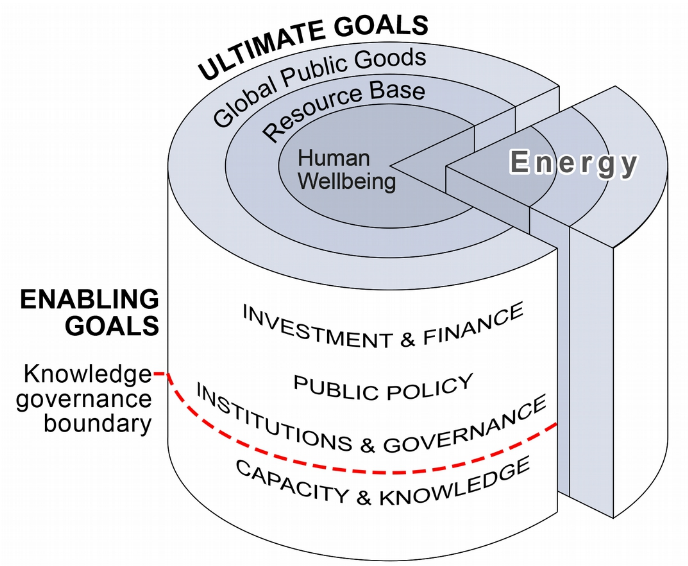

Figure 1. Sustainable development framework: three tiers of ultimate goals and four layers of enabling goals. Knowledge governance sits at the dashed line between the two base layers. Adapted from Nilsson et al. [1].

4. Review Methodology

The methodology for the review was to conduct a keyword text search for the string "knowledge governance" in the academic database SCOPUS, and the book catalogues of the National Library of Australia and the Australian National University, cross checked against the US Library of Congress. Titles, keywords and abstracts were included. The review focused exclusively on the use of knowledge governance as a single phrase, so all returns that were revealed as "knowledge, governance" or similar were rejected. Computer science literature, where knowledge governance has a technical meaning, was also rejected. For academic publications, only peer-reviewed material was included. Where keywords indicated knowledge governance but the phrase was not used in the title or the abstract of an article, it was rejected. Books with "knowledge governance" in the title were included, those without were examined for relevance in descriptions provided and/or table of contents.

This search strategy generated 47 articles and 3 books. They were grouped into private sector perspectives (31 articles and 1 book); public sector perspectives, including legal, policy and socio-political areas (15 articles and 3 books). Articles appear to demonstrate a growing interest and use of the term knowledge governance, from 1 article in 2001 and 2002, to 13 articles in 2013. Interestingly, for all the overlaps between well-established sustainability-related areas of inquiry described in the previous section, only two articles from this sample specifically related the term "knowledge governance" to sustainability. One of these [23] was developed from the original knowledge systems project mentioned in the introduction.

Each of these articles and books were analysed with a view to how they may inform the three nested sustainability goals of human well-being, resource base management, and global public goods. They were grouped into private and public sector perspectives; as indicted in the section outlining definitions of knowledge governance, these two literatures were quite distinct in their fundamental approach to knowledge governance, and so were best addressed separately.

5. Private Sector Perspectives

As indicated in the previous section, knowledge governance has received considerable academic attention in the private sector context. Early work by Grandori [42] drew linkages between knowledge and governance, with a particular emphasis on mechanisms for governing (setting institutional rules, incentives and processes) knowledge management activities. This was followed up by Foss and colleagues in the organisational economics context [32,33,43]. Foss's development of the concept [33] is tied to the private sector context, most clearly by using economic efficiency as the criterion by which to examine and assess knowledge governance. Foss presents an analytical approach that articulates how to go about investigating and analysing knowledge governance. He writes that knowledge governance "starts from the hypothesis that knowledge processes (i.e. the creation, retention and sharing of knowledge…) can be influenced and directed through the deployment of governance mechanisms, in particular the formal aspects of organization that can be manipulated by management, such as organization structure, job design, reward systems, information systems, standard operating procedures, accounting systems and other coordination mechanisms" [33]. These are described as critical antecedents to the conduct of knowledge management processes. However, the primary concern of the knowledge governance approach proposed by Foss is to examine these organizational or institutional characteristics in relation to their effects on individuals' behaviour and choices. In Foss's words: "governance mechanisms are, of course, deployed in the belief that influencing the conditions of actions…in a certain manner will lead employees to take those decisions… that, when aggregated…lead to favourable organizational outcomes" ([33] p. 36). Important to note here is that these governance mechanisms are seen as the product of deliberate "deployment", in other words, they are not taken as given features of an institutional environment, but as structures and rules put in place to achieve certain goals.

Michailova and Foss's work [32], combined with that of Grandori [42], laid the foundations for a range of cases that developed the concept of "knowledge governance mechanisms (KGMs)". This work applied the knowledge governance concept to learn how different approaches to knowledge-based processes and relationships enhanced (or didn't enhance) firm creativity, innovation and ultimately, profitability. One case showed that mechanisms to enhance knowledge sharing based on a concept of transactions can actually increase individuals' hostility towards knowledge sharing, while those based on commitment were more successful [44]. Another [45] highlighted how knowledge governance can help firms organise to identify 'valuable' problems and search efficiently for their solutions. They argued that complex, ill-structured problems require very different governance arrangements than comparatively simple problems, where authority-based hierarchies become less efficient at finding solutions, the more complex the problems become. Similarly, a case study of a large, complex aerospace R&D collaboration [46] concluded that in complex cases knowledge governance may be more effective the more flexible it is. Rather than seeking the 'best' knowledge governance mechanisms, the authors suggest knowledge governance should adapt as the innovation process proceeds. This resonates strongly with adaptive governance approaches to complex social-ecological systems.

Research in China has examined knowledge governance in relation to the guanxi effect, the complex networks of interpersonal obligations and commitments that characterise Chinese business relations [47]. The authors found that guanxi partly mediated the relations between knowledge governance strategies and knowledge sharing actions. This highlights that cultural norms can play an important role in knowledge governance.

The private sector literature shows that active knowledge governance is relatively new, with only a small amount of empirical testing and theory development. It does, however, highlight some key features of knowledge governance in relation to the 3 tiers of sustainability goals. First, even at the scale of firms and businesses, knowledge governance operates within socially and culturally shaped contexts. The role of interpersonal networks and individual agency remains important, but embedded within broader institutional norms. Second, the private sector interest in knowledge governance stems from seeking ways to enhance knowledge creation and to best capitalise on it. In the organisational economics context, this is driven by enhancing efficiency and comparative advantage; in the sustainability context, it can help to foster new solutions to natural resource-base challenges. The private sector literature suggests that actively deploying knowledge governance mechanisms can help foster knowledge creation and innovation. Third, the private sector knowledge governance perspective has started to make inroads on frameworks and analysis to help practitioners choose between different knowledge-based processes, based on different kinds of problems. More complex problems of sustainability may require quite different knowledge governance from simple problems.

6. Public Sector Perspectives

The public sector, legal and socio-political perspectives take a more critical approach to understanding and influencing knowledge governance than the private sector. While the private sector emphasis was largely on "mechanisms" to enhance knowledge processes and practices, the public sector perspective more commonly examines existing legal and socio-political knowledge governance through a critical lens. The public sector approach looks predominantly at the public regulation of private sector activity, from a perspective of protecting the public interest.

Knowledge governance in this context examines the tensions inherent in the need to protect 'private' knowledge as an asset to encourage innovation, alongside the public interest in accessible knowledge and the benefits from such innovations. In a major study of patent law, Drahos demonstrates the inequality of the 'global' knowledge system that is dominated by a small number of large patent offices [48]. He argues that their ability to create a knowledge governance system that favours the interests of transnational corporations is extended through 'technocratic trust', assisting developing countries to establish rules and procedures that favour the same groups.

In another major contribution drawing from evolutionary economics, patent law and other intellectual property regulation, the edited volume by Burlamaqui et al., Burlamaqui [35] places knowledge governance as an approach for re-thinking innovation and creativity, and how it may best be fostered in societies increasingly characterised by open source, inclusive knowledge practices. They are concerned with the question "how should government-issued intellectual property rules and regulations interact with competition policies, publicly funded R&D and other forms of technology policy in order to help craft and govern socially inclusive development strategies?" ([35] p. 6). They highlight the "tension and potential trade-off between private interests and the conception of knowledge as a global public good" ([35] p. 10). This trade-off relates directly to the sustainability framework and will be returned to later. In a later chapter in the same volume, Wilbanks and Rossini [49] use knowledge governance to shed light on why academia has been relatively slow to embrace distributed innovation such as open source publishing and wiki-style communications: "rewards, incentives and metrics for academic professionals are deeply tied to print-based metrics like citations, references and impact factors. The existing systems of knowledge governance and credit allocation are not well aligned with a distributed knowledge creation environment, and the kind of authority rewarded in academia (typically resulting from award of advanced degrees) is not always the same kind of authority rewarded in a distributed knowledge system". These studies point to the direct interplay between knowledge governance and creativity, innovation, access and sharing.

Lemmens [50] works through these issues in a critical analysis of how regulatory and legal structures shape the knowledge governance landscape in development and provision of new pharmaceutical drugs. She argues that the current knowledge governance arrangements favour industry to the detriment of populations who are excluded from the benefits of pharmaceutical discoveries due to proprietary law and regulation. She goes on to suggest that human rights obligations may be leveraged to challenge the existing governance of pharmaceutical knowledge, drawing particularly on the formalised human right to benefit from scientific progress. In an argument highly relevant to the sustainability framework, she contends that pharmaceutical knowledge should be regarded as akin to a public good, but that the global nature of knowledge production limits national capacities to regulate how that knowledge is shared or applied. Taking a human rights perspective highlights the rights of individuals to be able to exercise informed choice in relation to their health, and the role of knowledge governance in allowing or preventing such informed choice.

At the less legalistic end of the socio-political spectrum knowledge governance is related to the concept of "knowledge politics" described by Stehr as "strategic efforts to move new scientific and technical knowledge, and thereby the future, into the centre of the cultural, economic and political matrix of society" ([51] p. X). This edited volume analyses knowledge-related legal and policy processes from the perspective of broader social, political and philosophical agendas. For example, Fuller argues that the thrust of the concept of knowledge governance (as opposed to knowledge management or government) indicates a collective and conscious endeavour that has autonomy from management and government, and hence that 'knowledge-bearing institutions' such as universities play a special role in self-regulating the governance of knowledge [52]. This has indeed played out in controversies over science, such as the so-called "climategate" scandal, where universities and related academic institutions sought to both defend and reform the governance of academic knowledge in response to external challenges [53].

Taking a less regulatory approach, Gerritsen et al. propose knowledge governance can be regarded as a form of governance, like 'network governance' or 'adaptive governance', rather than the governance *of* knowledge [34]. These authors see knowledge governance as an avenue for social change (see definition earlier). This leads them to identify a set of principles for knowledge governance such as self-organisation, transdisciplinary knowledge production, social learning, reflexivity and boundary management. Interestingly, these principles share many characteristics with approaches to sustainability science [54–56], although this connection is not made explicitly by Gerritsen et al. Their approach highlights the importance of learning as a fundamental 'knowledge process', a point that was rare in the previous studies that favoured terms like 'knowledge creation and sharing', but relates to the substantial sustainability literature on social learning [57]. In their application of their conception of knowledge governance to a case study of Dutch farmers, they highlight the importance of a collaborative approach to innovation and change, but also that they encountered resistance to social change based on entrenched views and habits of the communities involved.

In the first of the two studies in this review to directly relate knowledge governance to sustainability, Manuel-Navarette and Gallopìn [23] apply the concept analytically to agricultural research in Argentina. They document how a particular research agency transformed its knowledge-based processes from a simple, linear model of technology transfer to more complex knowledge governance arrangements that drew on a network of public and private actors, including universities and farmers' organisations. This network supported a highly effective strategy to promote no-till agricultural practices, and contributed to the rapid adoption of this method, from 2% to 66% of cultivated area between 1984 and 2006 (in 2006 the world average area of no-till cultivation was 6%). They highlight the ways in which a shift from a 'vertical' knowledge governance structure to a more 'horizontal' network arrangement increased the knowledge flows around no-till agriculture, and suggest that the development of effective public-private partnerships to facilitate these knowledge flows were crucial. The second sustainability-related study [58] examined how collaborative sustainability research approaches sought to include local knowledge on water management, but prevailing academic conventions led to that knowledge being aggregated and standardised to conform to conventional standards of "epistemic authority", thereby losing its complexity and nuance.

The variety of perspectives, theoretical developments and applications shows that knowledge governance as a concept reflects its multiple origins, but also indicates a core set of ideas that remain reasonably consistent—enthusiasm for opportunities to design and manipulate knowledge processes for desired outcomes, coupled with an understanding of the broader constraints of the socio-political knowledge governance landscape. Both public and private sector perspectives demonstrate that existing knowledge governance arrangements, which are often embedded in broader institutional frameworks such as performance reward systems, economic imperatives, commercial law, or scientific norms, can impede or hinder the achievement of those goals. Understanding existing constraints imposed on knowledge processes, as well as strategies and institutional interventions for improving them, may hold considerable promise for addressing the "persistent gap" between knowledge and action for sustainability. This is where we now turn.

7. Implications of Knowledge Governance for Sustainable Development

In this section I will analyse the points that emerged from the previous review in relation to the three tiers proposed by Nilsson et al.: human well-being, resource-base management and global public goods.

7.1. Human Wellbeing

How might knowledge governance contribute to human wellbeing? In presenting well-being in their framework, Nilsson et al. express the importance of wellbeing as an individual, rather than an aggregate pursuit: "opportunity for each individual to pursue wellbeing and freedom". Dasgupta, cited in Nilsson et al. [1], included 'knowledge' as one of the determinants of wellbeing. The role of knowledge governance with regard to human well-being can therefore be regarded as facilitating opportunity and access to the knowledge-based processes that enable wellbeing.

The literature reviewed here offers some insights into the relations between institutions and governance and knowledge in the context of individual human wellbeing. There are clear wellbeing benefits from ensuring equitable access to the products generated by knowledge intensive practices such as research. Lemmens' [50] argument in relation to access to pharmaceuticals (knowledge-intensive products) is that access to these products enhances wellbeing through health. However recognising the right to knowledge itself, as a direct determinant of wellbeing, suggests that opportunities to learn and make informed decisions is a broad concern of sustainability in its own right. The trade-offs between proprietary knowledge and public access speak directly to the role of knowledge governance in ensuring citizens have the freedom and opportunity to pursue wellbeing through access to knowledge. The example of no-till farming uptake demonstrates the specific opportunities that can be opened up by reforming knowledge governance institutions to support collaborations and connections between farmer associations, research institutions and producers. Evaluating whether and how access to knowledge contributes to wellbeing may be a promising area for sustainability research and practice.

7.2. Resource-base Management

As it becomes more urgently recognised that complex sustainability challenges require creative solutions [59], it would seem that knowledge governance to facilitate creativity and innovation in resource-use efficiency and transitions away from resource-intensive development is needed [21]. The literature confirms the sustainability science view that knowledge-based approaches that support collaboration, connections and learning appear to be better suited to addressing complex problems. More open, networked, horizontal approaches to organising knowledge processes facilitate collaboration and learning across interconnected groups. Within both public and private sector applications of knowledge governance, there was a recognition that protective approaches to knowledge that are 'hostile' to sharing stifle the development of more efficient outcomes. The private sector literature highlighted that knowledge governance can be used at organisational scales to encourage innovation and knowledge sharing, although empirical work in this area is in early stages.

At a broader scale, the public sector analyses showed knowledge governance shapes incentives or disincentives for creativity and innovation. Yet it also placed knowledge governance actions within a broader social and institutional context that remains largely hostile to knowledge sharing. Finding the most productive balance between openness for innovation and creativity and the privatisation of knowledge for profit ('inclusive' versus 'exclusive', to use Burlamaqui's [35] terms) is a core knowledge governance challenge that flows through legal and socio-cultural avenues to permeate sustainability. From resistance to collaborative approaches by communities culturally embedded in existing knowledge practices to paper-bound academic reward systems and transnational corporations that exercise sophisticated strategies to maximise their gain from intellectual property, the broad context continues to favour exclusion over inclusion. Sustainability efforts to foster innovation and creativity through collaboration and openness should be understood to be struggling against these larger forces.

7.3. Global Public Goods

Finally, in relation to global public goods, the concept of knowledge as a global public good appeared in the literature both directly and indirectly. As noted in the Public Sector Perspectives section, Burlamaqui described the tension between knowledge for private gain and knowledge as a global public good. The overall struggle to reassert knowledge in the public interest across a wide range of social issues noted above, places sustainability efforts to support more collaborative approaches in a context of much broader political tension over what knowledge governance should be aiming for.

This issue has received attention in relation to sustainability. In their examination of whether current intellectual property rights help or hinder the production and dissemination of knowledge to address global sustainability challenges, Claude Henry and Nobel Prize-winning economist Joseph Stiglitz conclude that "the current global intellectual property regime, as well as serving the interests of the international electronic and pharmaceutical companies, is an impediment to the kind of global cooperation necessary in so many arenas, especially in development, global health, and even addressing the problems of global warming. Nor is it good for global science" ([59] p. 245). While they do not use the phrase "knowledge governance" (and hence were excluded from the previous sections of this review) their arguments relate strongly to those of the public sector knowledge governance perspective outlined earlier. They argue for a more holistic view of innovation systems that reform intellectual property laws and open up to other types of knowledge governance that stimulate and support innovative solutions to global sustainable development challenges.

The findings from this review in relation to the three tiers of Nilsson et al.'s model of sustainable development are summarised in Figure 2.

Figure 2. Knowledge governance for sustainable development—a framework for future research.

Analysing the findings of the review in relation to the layer cake framework demonstrates not only that knowledge governance is relevant to sustainable development, but also that it relates across the three scales of Nilsson et al.'s [1] model. From individual wellbeing and rights to organisational and institutional structures, through to global scale innovation systems, the knowledge governance literature presents a multi-scalar suite of issues. It helps to explain the 'persistence' of science-policy gaps [9], as efforts to overcome these gaps at project or organisational scales come into contact with broader social, cultural and legal systems that favour exclusion and private gain over inclusion and collaboration. This framework offers guidance to further examine this broader context of knowledge governance in relation to sustainability.

8. Limitations and Adaptations

In terms of the methodology of the review, there are immediate limitations in the scope of the material. For example book chapters that sit within volumes that did not have 'knowledge governance' in the title were not revealed through the search strategy. Material that was conceptually related but did not use the specific term of knowledge governance was also excluded, which helped to focus the study but meant that a wide range of associated topics were not covered. Grey literature was also excluded.

Conceptually, this review was deliberately limited to consideration of knowledge governance as a stand-alone concept. There are, of course, many overlaps with domains of sustainability-related research that are close but only summarily alluded to, such as adaptive governance and science and technology studies. Similarly, there is a fuzzy line between knowledge governance and knowledge management, which was particularly evident in the private sector literature. Hence one might argue that there are plenty of equivalent strategies or practices in the sustainability domain that speak to this fuzzy boundary. This is not denied here—as a researcher involved in science-governance connections I am aware of many institutional and organisational innovations that have been made to facilitate better relationships between knowledge and practice [8,22]. Yet these are typically not presented as knowledge governance interventions or strategies. The point of this review was to examine specifically what knowledge governance as a concept might add to these areas of scholarship and practice.

There are likewise other related issues that readers may feel should be incorporated into the model presented in Figure 2 (education, empowerment and participation, de-coupling, adaptation come to mind, and there are no doubt many more). Incorporating these in any meaningful way would have been counter to the aim of keeping the governance of knowledge front and centre. Hopefully, this review may encourage others to examine more specific connections between established sustainability concepts and issues and the governance of knowledge processes.

9. Conclusion

The aim of this review was to answer the question: "can interdisciplinary knowledge governance literature contribute to understanding and analysing the institutional knowledge-based dimensions of sustainable development?" By analysing the existing knowledge governance literature through the construct of Nilsson et al.'s sustainability model [1], I have shown that knowledge governance offers a conceptual basis from which to think critically about knowledge processes as foundational to sustainable development, and to consider how they are shaped and influenced by formal and informal institutions. By bringing the governance of knowledge to the fore (rather than regarding knowledge as an input to other governance goals), a range of opportunities and constraints have emerged. Far from there being a 'gap' between knowledge and action, this review suggests that this space is thick with institutional arrangements that have little to do with sustainability, but still strongly shape the knowledge-action landscape. This includes current formal and informal rules that tend to favour exclusion over inclusion, convention over innovation, and knowledge as a private asset rather than a human right.

The opportunities for enhancing sustainability outcomes through the knowledge governance domain are many [59]. From the deployment of knowledge governance mechanisms for greater efficiencies, to organisational and institutional reforms for enhanced innovation, to considerations of access to knowledge as a human right or a global public good, it brings the many rules shaping the dynamics of knowledge creation, sharing, access and use into consideration as a fundamental issue in sustainable development. It demonstrates that researchers may be able to develop knowledge governance strategies that address persistent challenges in sustainability, especially around access, innovation, and the re-conceptualisation of knowledge as a global public good. But more importantly, it places the challenges of doing so in a broader governance context.

Ultimately, the usefulness or otherwise of the concept of knowledge governance will be demonstrated in its application as guiding theoretical framework for sustainability research and implementation. Quantitative research could design metrics for assessing and comparing the sustainability impacts of different knowledge governance arrangements, as has been done in the private sector [47]. Empirical case studies could test the effects of new institutional arrangements on knowledge governance, and gather and compare different strategies for brokering or designing knowledge processes in the light of existing governance arrangements. Qualitative research could identify key constraints and facilitators to the effective application of knowledge either within or across organisations or sectors, considering the wide range of knowledge governance arrangements that affect practice. Such research would need to emphasise the practical utility of knowledge governance: has it helped researchers and practitioners to identify new interventions towards sustainability? Has it helped to enhance their functionality or performance? Has it helped people to navigate the difficult terrain that connects knowledge and action, and to generate new options for reconfiguring that landscape? Positive answers to these questions would support the rationale for viewing knowledge governance as underpinning efforts to achieve sustainable development, and start to build theoretical and practical tools to enhance these processes.

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Challenges in Sustainability | 2013 | Volume 1 | Issue 2 | Pages 94–103
DOI: 10.12924/cis2013.01020094

Challenges in Sustainability

Research Article

Carbon Intensities of Economies from the Perspective of Learning Curves

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Submitted: 25 September 2013 | In revised form: 3 February 2014 | Accepted: 9 February 2014 |
Published: 26 March 2014

Abstract: While some countries have achieved considerable development, many others still lack access to the goods and services considered standard in the modern society. As CO_2 emissions and development are often correlated, this paper employs the theoretical background of the Environmental Kuznets Curve (EKC) and the learning curves toolkit to analyze how carbon intensities have changed as countries move towards higher development (and cumulative wealth) levels. The EKC concept is then tested with the methodology of learning curves for the period between 1971 and 2010, so as to capture a dynamic picture of emissions trends and development. Results of both analyses reveal that empirical data fails to provide direct evidence of an EKC for emissions and development. The data does show, however, an interesting pattern in the dispersion of emissions levels for countries within the same HDI categories. While data does not show that countries grow more polluting during intermediary development stages, it does provide evidence that countries become more heterogeneous in their emission intensities as they develop, later re-converging to lower emission intensities at higher HDI levels. Learning rates also indicate heterogeneity among developing countries and relative convergence among developed countries. Given the heterogeneity of development paths among countries, the experiences of those which are managing to develop at low carbon intensities can prove valuable examples for ongoing efforts in climate change mitigation, especially in the developing world.

Keywords: carbon emissions; development; EKC; learning curves

1. Introduction

Higher income levels have been traditionally correlated with increased energy consumption and higher carbon emissions in industrialized and developing countries alike. As climate change awareness grew during the 2000s, interest in using alternative, renewable energy sources in order to reduce dependence on fossil hydrocarbons rose.

While efforts have been made to de-link energy from carbon emissions, the bulk of energy production in the world continues to be linked to carbon-emitting sources [1, 2]. As initially presented by Kaya [3], the enduring prevalence of fossil fuels in the global energy mix binds together economic activity, energy usage and carbon emissions which continue exacerbating the risks for climate change. The problem is compounded since international negotiations towards a more widely-reaching climate agreement than Kyoto have been beset by slow progress, particularly in the last COP meetings in Copenhagen, Cancun, Durban, Doha and Warsaw [4, 5]. In an escalating blame-game, countries criticize each other for being lax in their pollution (and emissions) controls, with some even threatening to retaliate in international trade—in the absence of better multilateral solutions—with the introduction of border carbon adjustments or similar mechanisms [6].

As of 2013, countries differ not only in their level of development, but also in terms of their share of renewable energy, the energy and carbon intensities of their economies, and policies applied to enhance environmental protection and sustainability. Stepping aside from the debate around international climate negotiations, one of the key environmental issues—CO_2 emissions in the atmosphere due to energy production—profits from good available statistics which allow it to be measured and correlated with macroeconomic indicators.

While the correlation between economic growth and carbon emissions is nothing new to environmental practitioners, this paper contributes to the international emissions debate by examining the carbon intensities of the major global economies employing the alternative optic of learning curves. While traditionally used to assess cost reductions as specific technologies are adopted, learning curves can also be used in socio-economic fields, such as examining the evolution of labour intensities of GDP through time [7, 8]. Based on data from IEA [9], this paper uses economic performance and CO_2 emission statistics to look at countries as if they were industries which would be expected to reduce their carbon intensities throughout time. Specifically, the paper estimates how fast major economic regions, as well as the world as a whole, have reduced emissions based on cumulative economic output between 1971 and 2010. This examination is followed by a discussion of the possible reasons behind the different learning rates for reduction of carbon intensities found for different world regions.

2. Heterogeneous Development Paths

Back in the 1960s economists found an apparent correlation between income levels and inequality in national economies [10]. Observations showed that inequality appeared to rise with economic growth, particularly in the early stages of a country's development, up to a point when it started to decline. The shape of this correlation has been known as the inverted "U" curve, or simply the Kuznets Curve [11].

More recently, the same concept has been extrapolated to environmental economics and named the Environmental Kuznets Curve or EKC [12]. Analogous to the original concept, the EKC asserts that pollution increases with development up to a certain level, after which it declines ([13], p. 2). The existence of EKC relations, however, have been a matter of scientific debate. An overview of proponents and critics of the EKC has been made by Stern [14]. One of the main criticisms is outlined by Arrow et al. (1995, [15]) who criticize the EKC's inherent assumption that there exists a sustainable system in which environmental damage is not captured so as to reduce economic activity, income and, eventually also the growth process. Others argue that EKC relationships might be only expressions of the effects of trade, different shares of services in national economies, and the distribution of polluting industries between countries [16]. Brajer et al. (2008, [17]) also noticed that the appearance of an inverted U shape configuration in the EKC is highly dependent on which indicators are chosen to describe environmental degradation.

As such, the EKC concept has obvious shortcomings and has not been verified for all sorts of environmental degradation. While the concept is intuitive and elegant, it can be misleading, causing policy makers to think that the solution for climate change is simply to "get rich" and overcome emission-intensive transition stages once higher development levels have been achieved [18]. A plot of carbon intensities of the economies of 138 countries compared to their Human Development Indexes (HDI) is presented in Figure 1.

It becomes evident that the poor fitting of the logarithmic trend line (R^2 = 0.18) puts into question the validity of an inverted U-shaped pattern for the relationship between HDI and CO_2 emissions per dollar of output. In other words, many countries have seen an increase in quality of life without a corresponding increase in the carbon intensities of their economies. Thus, human development alone is no guaranteed solution for the climate problem. In theory, increased HDI could actually be harmful for the climate system since many developing countries are found in the high end of Figure 1 with no guarantee that their trajectory will take them down to the right end of the curve. At the same time, it is worth observing that many countries are managing to increase their welfare (towards higher HDI) at lower emission intensities as indicated by the large number of dots on the lower end of the curve [19, 20].

Countries on the right lower end of Figure 1 suggest that as countries get richer, they can invest in environmental improvements and reduce their emissions. However, the large dispersion among developing countries among which "high learners" figure close to "bad performers", leave room for some discussion. Since, in the developing world, countries are delivering similar standards of living to their citizens at different levels of emissions, they apparently do so at different levels of environmental costs (measured in GHG emissions).

There are just too many exceptions to the idea that development leads to low emission intensities. This prevents a generalization based on the traditional view of the EKC rule on development paths.

Overall, countries have achieved substantial progress measured by improvements in their HDI during the last decades, and this can be seen in the latest reports on the millennium development goals [21]. Virtually all countries in the world advanced their HDI rankings, albeit not at the same pace. A similar pattern, however, could not be observed in their emission reductions per unit of economic output. Figure 2 adds a dynamic component to the plot made in Figure 1, in the sense of analyzing what happened between 1980 and 2007, in the form of a 138-country intertemporal plot of HDI against emissions per unit of GDP. The plot focuses on three select groups: (1) The world average, (2) BRICs [22] and (3) Scandinavian countries (as a proxy of advanced economies).

While Scandinavia experienced dramatic reductions in carbon intensities, the overall world figures indicate only a

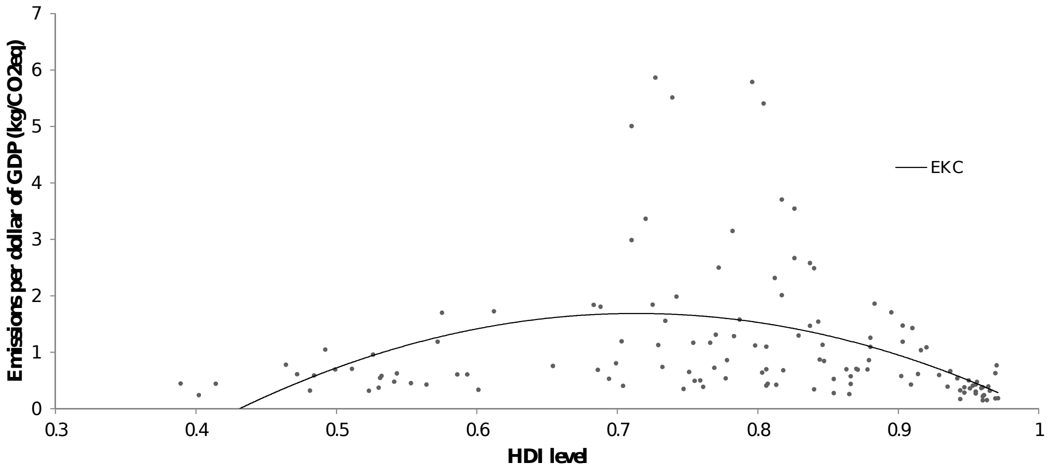

Figure 1. Emissions per dollar of GDP (2010) plotted against HDI for a sample of 138 countries. Sources: developed by the authors based on data from the United Nations Development Programme and the International Energy Agency.

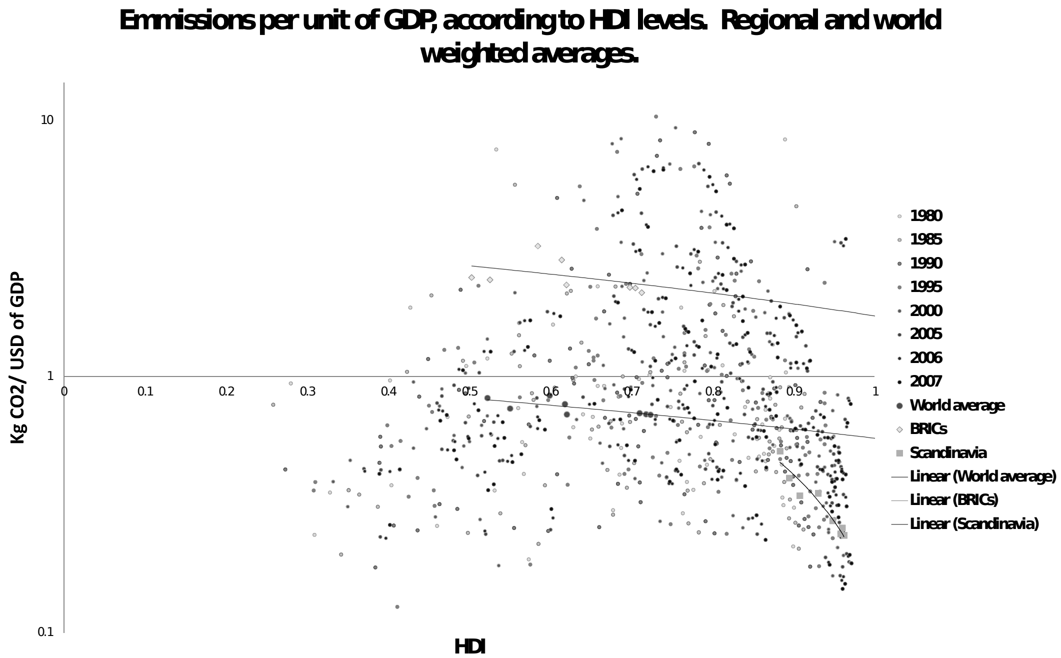

Figure 2. Emissions per unit of GDP plotted against HDI levels, 1980–2007. Plotted are 138 countries during 8 sampled time periods. Regional and world weighted averages according to respective populations. Based on data from IEA and United Nations Development Programme (2007).

modest decrease in this parameter. This is especially evident in the BRICs, which had emissions figures above the world average during the period analyzed (1980–2007).

Previous literature suggests that countries cannot rely on development alone to drive down CO_2 emissions. Similar to propositions by Tierney (2009, [18]), the answer lies in two underlying aspects of development: that development paths can present mutual-dependency between different countries; and overall system constraints.

2.1. Trade and Mutual Dependency between Countries

Mutual dependency means that the very driver of globalization—specialization in comparative advantages expressed by international trade—can lead to more rigid emission patterns for some countries than others. At the same time, the movement of goods between countries can be key for some economies to be able to reduce their emission intensities. As noted by Suri and Chapman (1998, [13]), exporting countries can increase their emission intensities while importing countries can reduce their emission intensity. Hamilton and Turton (2002, [23]) noticed that by having a larger share of the service sector in the overall economy, some countries can manage to outsource emissions while still retaining profitable economic activities inside their markets. It is important to bear this in mind, as the low emissions per unit of GDP in Scandinavia may be not only the result of shifts towards renewable energy or higher energy efficiency, but also of emigrated emission-intensive to other regions of the world [24, 25].

2.2. System Constraints

Similarly to what has been proposed by [26], environmental systems constraints determine the operating space for humanity. This implies a maximum amount of emissions that can be absorbed by natural sinks without triggering costly climate change. Thus, even in the absence of the mutual dependency issue discussed above, it would not be an option to simply wait for emissions per unit of GDP to go down to a "safe" threshold. According to data from the International Energy Agency [27], developing and least developed countries (HDI < 0.89) comprise 84% of the world population. The global carbon budget will have long since expired as the economies of these nations approach Scandinavian emission levels. In other words, in a business-as-usual trajectory, HDI values will most likely retrocede if a fossil-intensive path is pursued by the populous developing world [19].

Finally, even with the positive indication illustrated in Figure 2 that emissions per dollar of GDP are falling for the world as a whole, this will not be enough to hedge against climate risks because two other factors cancel out the gains of reduced global carbon intensity by a large degree. Figure 3 shows that climate damage has four dimensions: while carbon and energy intensities are on average decreasing, total world GDP and population are growing steadily [28]. Average emissions per unit of GDP have fallen 24% between 1971 and 2008 (from 0.92 to 0.70 kg CO_2 eq/dollar of GDP) while the world population has practically doubled from 3.4 billion to 6.6 billion in the same period. Global wealth followed the same trend (323% increase since 1971). So while the world economy makes cleaner dollars today, it makes so many of them that the aggregate level of emissions has grown exponentially.

This can be illustrated by the relationship proposed by Kaya (1997, [3]), which is a useful tool to understand the human impacts on the climate system. The Kaya equation incorporates indicators which declined over the period between 1971 and 2008 (energy and carbon intensities), comparing the overall impact of these efficiency gains with the growth in wealth (GDP) and population during the same period. Although simple, the relation is a good representation of the magnitude of human emissions on the climate system. The Kaya identity focuses on CO_2 emissions from anthropogenic sources and is expressed as follows:

$$F = P \times \left(\frac{G}{P}\right) \times \left(\frac{E}{G}\right) \times \left(\frac{F}{E}\right) \quad (1)$$

or

$$F = P \times g \times e \times f \quad (2)$$

where F is global CO_2 emissions from human sources, P is global population, G is world GDP and E is global primary energy consumption. Then, $g = \left(\frac{G}{P}\right)$ is the global per-capita GDP, $e = \left(\frac{E}{G}\right)$ is the energy intensity of world GDP and $f = \left(\frac{F}{E}\right)$ is the carbon intensity of energy.

The Kaya identity suggests that damage to the climate system is directly proportional to the global population (P), the wealth of these individuals (g), the amount of energy used to run each unit of the economy (e) and the carbon-footprint associated to every unit of energy produced (f). With growing population and wealth, emissions increase when material flows in the economy are enabled by energy sources that emit carbon (thus creating an impact on the environment). Figure 3 uses data from IEA to provide empirical illustration to the Kaya identity, showing that any efficiency gains in emissions and energy usage have been clearly offset by growing populations and wealth at a global level.

With evidence indicating a growing human impact on the climate system, more attention should be given to countries entering more intensive development stages. Given their large populations, developing countries will have to play a major role in an eventual reduction of overall emissions and stabilization of greenhouse gas concentrations affecting the climate system. As previously discussed and demonstrated in Figure 1, GDP and HDI indicators do not correlate to confirm an EKC relationship, and thus development as pursued in past decades will not lead us to a safe trajectory. In the next section, we will try an alternative approach in search of a pattern between emissions and development. In order to capture some of the dynamic effects which occurred between 1971 and 2008, we this time use the concept of learning curves, calculating the learning rates (the rate at which reductions in the carbon intensity occurred) for each individual country.

3. Learning Rates for Carbon Intensities of World Economies

The concept of learning curves—also known as experience curves—is conventionally used to represent an improvement in technology, such as production costs or efficiencies, along with associated experience or cumulative output [29, 30, 31]. Learning curves provide a graphical representation of changing rates of learning over time for a given activity. The concept is often used for specific industries, as costs of innovative technologies tend to decrease as experience is accumulated [32].

Examples of learning curve analysis often include specific technological sectors [33]. Studies have been made for photovoltaics, where the cost of solar electricity has been shown to decline as a function of the cumulative number of photovoltaic panels installed [30]. Another known example concerns biofuels, where Goldemberg (2004, [34]) showed a strong historical downward trend in Brazilian ethanol prices following the rapid increase in ethanol production and use in the country, which eventually improved the competitiveness of ethanol in relation to gasoline. The plot of learning curves often encompasses logarithmic scales.

The use of learning curves for the analysis of technological learning paths is subject to shortfalls as the curves usually fail to differentiate among the full range of components that contribute to a given technological solution [35].

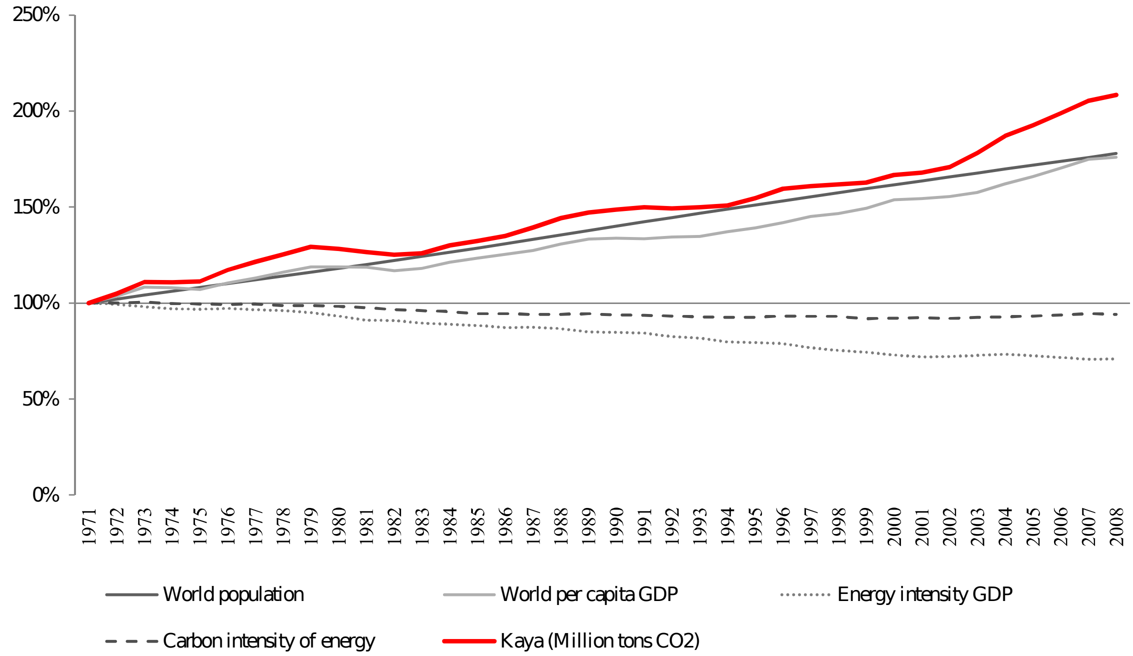

Figure 3. The calculated Kaya index (total anthropogenic CO_2 emissions in the climate system) and its components. While carbon and energy intensities have fallen since 1971, both total wealth and population are increasing, cancelling out the benefits of lower carbon intensity in the global economy. Source: calculated by the authors based on IEA [27].

Each component may follow a different learning path over time, thus affecting the overall path of the total solution. Another difficulty is to capture variations of learning rates over time [32]. Still, learning curves can be useful tools for strategic planning and for the analysis of technological performance or price variations over time.

In this section, we apply the concept of learning curves to analyze the development of carbon intensities in national economies. While a component-learning approach of sub-sectors of national economies would be the ideal approach, data limitations impose some analytical simplifications. Here, countries are considered to be production units with their output expressed in units of gross domestic product (GDP). Costs are considered to be the carbon intensities of national GDP, which can be interpreted as the environmental cost of generating each unit of GDP.

The theory behind the EKC suggests that the least developed countries may experience “negative learning” as their emissions are—still according to the EKC logic—expected to increase per unit of GDP produced; developing countries are expected to have low learning rates; and developed countries should display positive learning, indicated by a downward slope in their emissions per dollar (see Figure 4). Instead of a static analysis of the carbon intensities of countries for a single year, this section uses recent IEA data spanning from 1971 to 2010 to represent the learning process. Observations between 1971 and 2010 are used to calculate whether learning rates justify the hypothesis derived from the Environmental Kuznets Curve.

Based on Ferioli et al. (2009, [32]), the expression representing learning curves can be written as:

$$C(x) = C(x_0)\left(\frac{x}{x_0}\right)^{-L} \tag{3}$$

where x is the cumulative output, x_0 is the initial output, $C(x)$ is the carbon intensity at the cumulative output, $C(x0)$ is the carbon intensity at the initial output and L is the learning parameter. As the inclination of learning curves are based on learning rates (LR), these are expressed as:

$$LR = 1 - 2^{-L} \tag{4}$$

where LR is the learning rate, which expresses the rate of change in emissions per dollar of GDP from the first observation (1971) to the most recent observation available (2010), based on data from the International Energy Agency (IEA) published in 2010 [36]. For calculation purposes, (1) and (2) are combined in the final working expression:

$$LR = 1 - 2 \times \frac{log\left(\frac{C(x)}{C(x_0)}\right)}{log\left(\frac{x}{x_0}\right)} \tag{5}$$

While learning rates could be calculated for each of the 131 countries sampled, in this note we calculate the rates for the main macro-regions under the IEA classification [37]. Learning rates consider all intermediate years between 1971 and 2010, as a regression is made for the entire data set. A sample data plot for the world average is made on a double-log scale in Figure 5.

The results of the learning rates of decarbonization are shown in Figure 6.

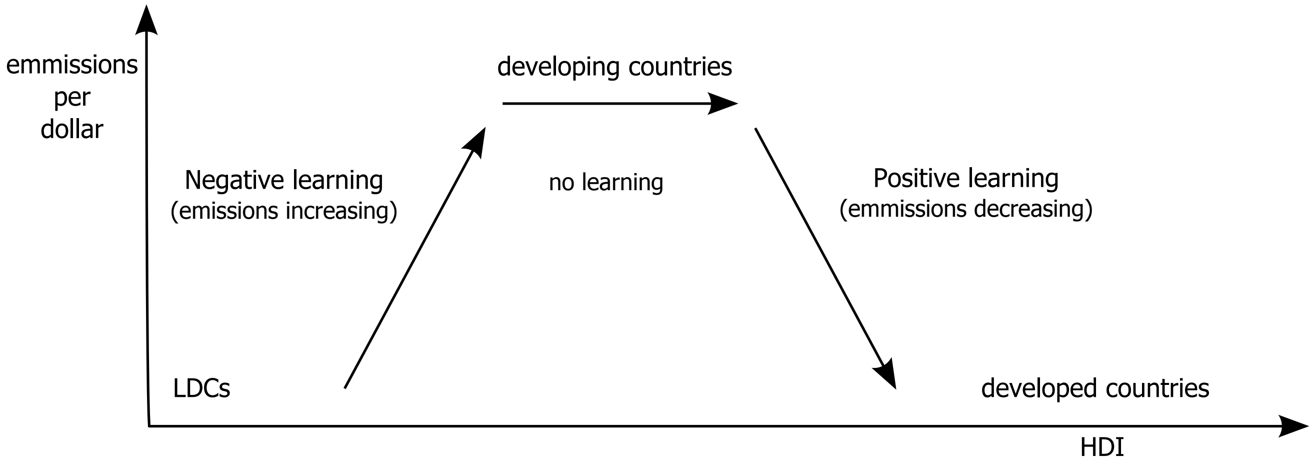

Figure 4. Hypotheses based on the EKC concept for the learning rate of decarbonization of economies.

Contrary to the hypothesis implied by the Kuznets logic, it is not evident from the data that least developed countries are linked to negative learning rates, developing countries with learning rates close to zero and positive learning rates for developed countries. Figures 5 and 6 indicate that although the world as a whole experienced a reduction in its carbon emissions per unit of GDP (1971 – 0.88 kg CO_2 per USD of GDP; against 0.59 kg in 2010), a number of individual countries have experienced negative learning. In other words, many countries increased their emissions per dollar during the period between 1971 and 2010. Countries which figure close to the range of zero learning include Brazil, Costa Rica, India, Tunisia and Mexico.

In line with the aforementioned hypothesis, countries which had negative learning generally belong to lower HDI classes, but also include exceptions such as wealthy oil-producing states, one EU country (Greece) and New Zealand. These exceptions indicate that the learning rates of decarbonization might be highly dependent of which sectors emerge as central in each national economy (e.g. mining, oil exploration), as well as how much of those emission-intensive resources are exported when compared to domestic consumption. This is relevant because even in the presence of international trade, current emissions statistics are bound to the country of occurrence, not to countries which import high emissions-intensive products or energy [38].

Finally, countries which had positive learning—those which effectively reduced the carbon intensity of their economies between 1971 and 2008—are the most difficult to interpret. As expected, most of the leading world economies figure among the “positive learners”, such as the USA, most European countries and Japan. However, the top positive learner is not a state with a high HDI, but instead China, which reduced its carbon intensities from 5.43 kg per dollar in 1971 to 1.79 in 2010. While a carbon intensity of 1.79 was still higher than the average world carbon intensity of 0.59 kg CO_2 USD^{-1}, China’s significant reduction in carbon intensity could be due to transformations in the national energy system (mostly based on coal use), but also due to factors beyond low-carbon policies, such as exchange rate dynamics between the Chinese renmibi and the US dollar [39].

4. Discussion

The rate of learning of reductions in the carbon intensities of economies depends on the starting point of each nation. For a country which started with high carbon intensities in 1971, it will be comparatively easier to reduce its emissions by 2010 than for another country which already had low carbon intensities in the initial period. This follows a similar logic to the catch-up effect in development economics, as proposed by Abramovitz (1986, [40]). For countries which already had low carbon intensities ($<$1.0 kg CO_2 USD^{-1}), further reductions are likely to be increasingly more difficult and more costly—supposing the existence of decreasing returns—if no structural change occurs. Obviously, if energy is increasingly sourced from low-carbon or carbon-free sources, further reductions in carbon intensities may nonetheless be feasible. Interestingly, the Latin American region managed to achieve an average carbon intensity of 0.58 kg CO_2 $^{-1}$ at USD 32 trillion in cumulative output, while OECD North America took USD 320 trillion in product to achieve the same carbon intensity levels.

Although the initial analysis of learning curves of macro regions apparently offers a stronger basis for an EKC interpretation, the strong variability in national carbon intensities between the years 1971 and 2008 makes trend lines of different regions difficult to compare. Factors such as the oil shocks in 1973 and 1979, the collapse of the USSR in 1990—1991, and varying levels of GDP growth over the years have contributed to this variability in emissions [41].

Some developing countries have shown progress towards low-carbon development paths. Examples include Mozambique, China and Colombia, all of which have implemented national policies aimed at the exploitation of bioenergy, hydropower and other potential sources which may have contributed to lowering their carbon intensities.

This diversity in development paths among developing countries provides rich ground for further investigations. While the inverted “U” curve pattern is weak for direct at-

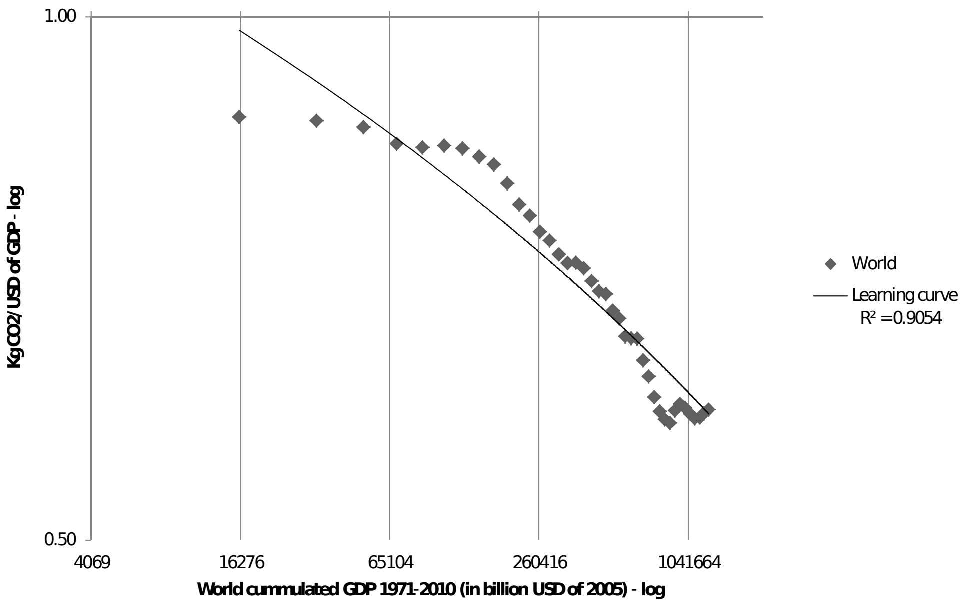

Figure 5. Learning curve for reductions in carbon intensity based on cummulative economic output. Aggregated data for the World. Source: authors calculations based on IEA [9].

tempts to represent an EKC (Figure 1), the measure of variability of carbon intensities per HDI group implies a more pronounced inverted "U" shape for the same data. This indicates a higher level of dispersion—here called heterogeneity—for developing countries. Figure 7 illustrates this, highlighting that values vary the most for countries in the HDI interval between 0.6 and 0.9, converging afterwards.

The existence of high dispersion in both carbon intensities and learning rates among developing countries hints at the existence of a plurality of development paths. As suggested by Burke (2012, [42]), this makes the case for policy studies among the developing countries with the lowest carbon intensities, as a way to better understand why some countries seem push ahead with their development with a relative decouple from carbon emissions.

Drawing lessons from successful cases of low carbon development paths is an urgent necessity for climate change mitigation efforts, which would enrich the toolkit of options available to strengthen—and facilitate—international cooperation related to climate change mitigation.

5. Conclusion

The last three decades were characterized by substantial improvements in human development, but this was achieved at a high environmental cost. The emergence of large countries such as China and India has put the future growth trajectories of the developing world in the global spotlight. It is now evident that emerging economies cannot follow the same carbon-intensive paths which current advanced economies once did, as this would most likely trigger negative environmental externalities that could cancel out gains in human development.

By using the theoretical background of the Environmental Kuznets Curve (EKC), we have explored whether empirical data supports an EKC relationship between development and emissions intensities of economies. The results indicated a weak correlation with the EKC considering carbon intensities and human development indexes (HDI). This indicates that there is no rule for dirty development in emerging countries, as the EKC fails to show a clear trend of increased emissions for countries undergoing intermediate development stages.

The discussion of the EKC for HDI and carbon intensities represents only a static view of development based on data from 2010. In order to obtain a glimpse of the dynamic effects of carbon intensity changes between 1971 and 2008, we have employed the instrument of learning curves. When applying the learning curves methodology to measure the speed on how countries reduce their emissions intensities as their cumulative GDPs double, this paper was able to show that there is also no empirical backing for an EKC relationship in learning. An EKC relationship in learning implies a hypothesis of negative learning (increasing carbon intensities) for the least developed countries, near-zero learning rates for developing countries, and positive learning rates (reduction in carbon intensities) for developed countries. The data, however, has challenged this hypothesis. For example, learning rates of economic decarbonization have been especially high for China (meaning emissions per dollar fell strongly for each doubling of GDP in the period analyzed). Negative learning has been observed, however, especially for areas in Africa and the Middle East due to their strong dependence on hydrocarbon usage and exports.

Interestingly, the inverted "U" pattern of the EKC held for standard deviations of carbon intensities of GDP per level of HDI. This suggests that developing countries are more heterogeneous among themselves in what concerns their carbon intensities. Their heterogeneity is particularly

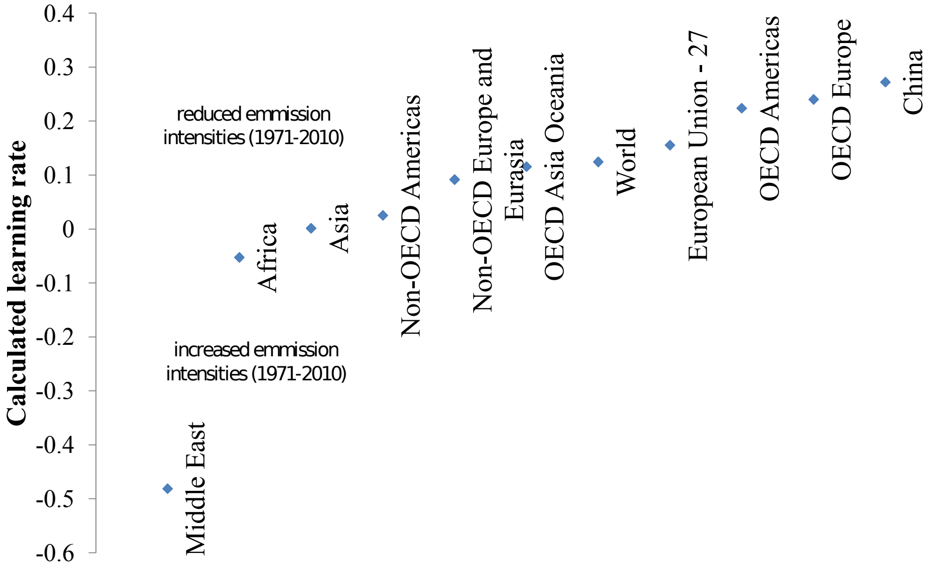

Figure 6. Calculated learning rates of reductions in emissions intensities. Considering macro-regions in OECD statistics between 1971 and 2010.

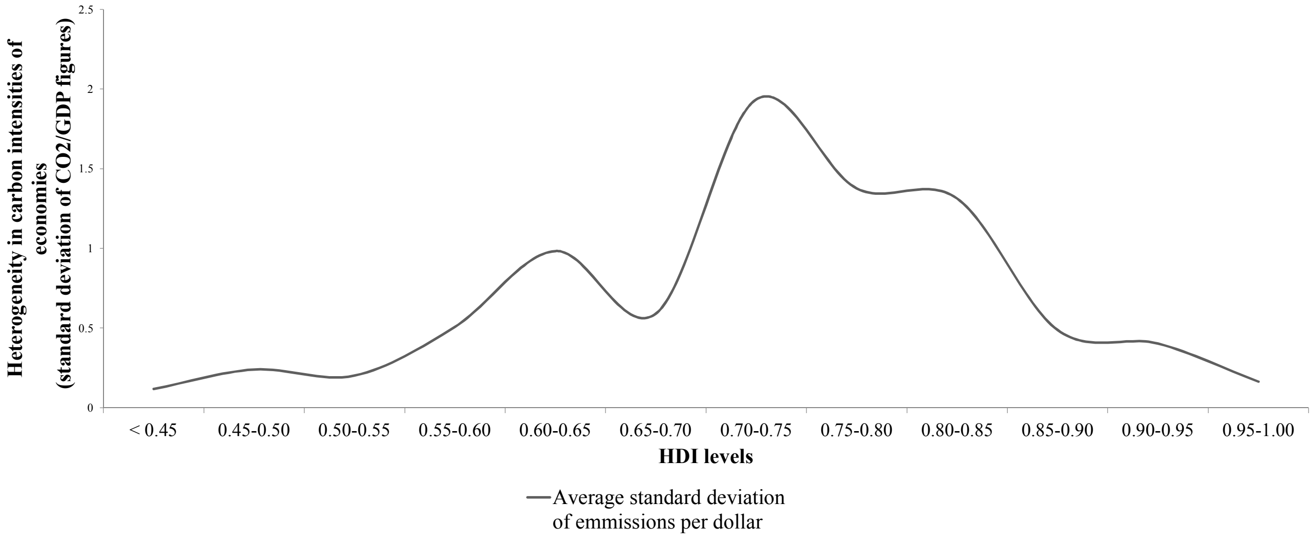

Figure 7. Standard deviation of carbon intensities of economies, as measured by kg CO_2 USD^{-1} according to Figure 1. Source: [9].

clear when compared to least and highly developed countries, since for those the statistics converge more visibly. A similar finding was presented by Steinberger (2002, [20]).

Although it cannot be said that countries grow more polluting during intermediary development stages, they do indeed become more heterogeneous in their emission intensity during such stages. A lack of direct observation of the EKC can be seen as a positive sign, since it suggests there is no unavoidable rule of carbon-intensive development paths for all countries. Instead, the curious results found for learning rates point to a plurality of decarbonization paths for the developing world. The identification of successful examples of low carbon development is extremely important, to providing a functional bottom-up approach for more effective international climate change negotiations.

The limits of the parameters chosen in this work must be recognized. Carbon intensities are very aggregated indicators of underlying factors such as fuel shares, energy intensity and economic structure (e.g. the share of service sectors, agriculture and manufacture within economies). Suggestions for further research include an analysis adjusted for economic structure and specific sectors of countries. In particular, studies examining what are the most important factors for national low-carbon development, as well as the transferability of those factors to developing countries. China could be an interesting case for in-depth examination, due to the fact that it has experienced strong industrialization and yet became the country with largest reductions in carbon intensities between 1971 and 2010 (Figure 6). Future studies could also attempt to disentangle the effects of policy-based low carbon paths from other phenomena, such as carbon leakage via regulatory competition in international markets.

Another suggestion for future studies would encompass the idea of mutual dependencies emerging from global trade patterns, since countries might find it more difficult to lower carbon intensities if their economies are specialized in emission-intensive manufacture for exports. The dispersion of carbon intensities and learning rates among developing countries could also suggest mutual dependency among developing countries due to increased south-south interactions. The verification of the latter is another fertile ground for investigations.

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