Ecological Economics 69 (2010) 2075–2084

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Global mechanisms for sustaining and enhancing PES schemes

Josh Farley [a,*], André Aquino [b], Amy Daniels [c], Azur Moulaert [a], Dan Lee [a], Abby Krause [a]

[a] Department of Community Development and Applied Economics, University of Vermont, Burlington, VT 05405, United States
[b] World Bank Carbon Finance Unit, United States
[c] US Forest Service, WO Research and Development, United States

ARTICLE INFO

Article history:
Received 24 September 2008
Received in revised form 22 January 2010
Accepted 22 February 2010
Available online 8 April 2010

Keywords:
Payments for ecosystem services
Carbon sequestration
Biodiversity conservation
Incentive mechanisms

ABSTRACT

An international payment for ecosystem service (IPES) schemes may be one of the only mechanisms available to stimulate the provision of vital non-marketed ecosystem services at the global level, as those nations that benefit from global ecosystem services (GES) cannot readily force other sovereign nations to provide them. Currently, international trade offers trillions of dollars in incentives for countries to convert natural capital into marketable goods and services, and few payments to entice countries to conserve natural capital in order to sustain critical non-marketed ecosystem services. We examine the biophysical characteristics of climate change and biodiversity to understand the obstacles to developing effective IPES schemes. We find that none of the existing schemes for providing GES are adequate, given the scale of the problem. A cap and auction scheme for CO_2 emissions among wealthy nations could fund IPES and simultaneously deter carbon emissions. To disburse funds, we should adapt Brazil's ICMS ecológico, and apportion available funds to targeted countries in proportion to how well they meet specific criteria designed to measure the provision of GES. Individual countries can then develop their own policies for increasing provision of these services, ensured of compensation if they do so. Indirect IPES should include funding for freely available technologies that protect or provide GES, such as the low carbon energy alternatives that will be essential for curbing climate change. Markets rely on the price mechanism to generate profits, which rations technology to those who can afford it, reducing adoption rates, innovation and total value.

1. Introduction

As described in the introduction to this special issue (Farley and Costanza, 2010-this issue), one of the most important problems our society currently faces is how to strike a suitable balance between the conversion of natural capital to economic production and its conservation to provide ecosystem services, both of which are essential to our well-being. One serious obstacle to striking a balance is the fact that ecosystem services provide benefits at a variety of spatial scales, ranging from the local to the global (see Balmford and Whitten, 2003; Ferraro and Kiss, 2002; Sandler, 1993 for estimates of relevant boundaries). Local efforts to provide ecosystem services are unlikely to consider global benefits, and global beneficiaries are prone to free-ride on local efforts. The likely result is an under-provision of global ecosystem services (Farley, 1999; Farley et al., 2007; Ferraro and Simpson, 2002).

Of the five mechanisms available for ensuring the provision of ecosystem services–prescription, penalties, persuasion, property rights and payments (Salzman, 2005)–only payments are likely to be effective at the global level. International law recognizes a nation's sovereign right to use its own natural resources as it wishes, which rules out penalties, prescription, and externally mandated changes in property rights. Low-income nations hold much of the planet's ecological wealth, and it would be difficult to persuade them to forgo the benefits of converting it to economic production in order to maintain global ecosystem services. Payment schemes in contrast impose fewer threats to sovereignty and are likely to be welcomed by low-income nations.

A number of international payment for ecosystem service (IPES) schemes exist, but their impact on ecosystem service provision remains negligible. Effective IPES schemes face several serious obstacles. First, such schemes require an institution capable of collecting payments from global beneficiaries, which confronts the typical challenges of international collective action problems (Balmford and Whitten, 2003; Ferraro and Simpson, 2002; Kaul et al., 2002; Sandler, 1998). Payments must at least cover incremental costs of service provision net of any local and national benefits, but should not exceed net global benefits (Daly and Farley, 2004; Olson, 1969). Unfortunately, international payments for the raw materials that serve as the structural building blocks for ecosystems, for agricultural products from converted ecosystems, and for the fossil fuels and mineral resources whose waste products destroy ecosystem services

* Corresponding author. Fax: +1 802 656 1423.
E-mail address: Joshua.farley@uvm.edu (J. Farley).

0921-8009/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.ecolecon.2010.02.016

totals nearly 4 trillion dollars per year (World Trade Organization, 2006). In comparison, direct international payments for the ecosystem services which that structure could otherwise provide, dominated by carbon markets (Huberman and Leipprand, 2006), are negligible: international payments for both carbon sequestration and emission reduction projects totaled just over 7 billion dollars in 2008 (Capoor and Ambrosi, 2009). Existing monetary incentives for allocating natural capital between economic production and vital ecosystem services are horribly lopsided.

Second, an effective IPES scheme would need to develop an efficient mechanism for disbursing payments in exchange for the provision of ecosystem services. Aside from carbon sequestration, most existing schemes pay for ecosystem services indirectly by supporting environmentally friendly commercial activities like certified logging, apiculture, or eco-tourism, but direct payments are likely to be more effective (Ferraro, 2001; Ferraro and Kiss, 2002). Where direct payment systems do exist, they typically fund specific projects with recipients chosen by centralized organizations, and the information required to decide between competing proposals is immense. Grant writing skills may play as much of a role in determining what projects are funded as the quality of the project itself, and transaction costs can be very high. An effective mechanism should minimize transaction, implementation and opportunity costs, which requires decentralized decision-making (Daly and Farley, 2004).

A third obstacle is the lack of well defined property rights within many countries, a prerequisite for effective market mechanisms, compounded by concerns in many nations about "ecological imperialism" and threats to sovereignty (Farley et al., 2007). Finally, our ignorance concerning how ecosystems generate services and how human activities affect them is a challenge for any PES scheme, and system uncertainty increases along with system boundaries. This makes it difficult to decide what activities PES schemes should pay for and the level of services provided by those activities.

This article proposes an IPES scheme for climate regulation and biodiversity financed by carbon auctions that addresses these problems. A carbon cap and auction system in the wealthy nations could generate dramatic increases in funding for mitigating climate change and biodiversity. Funds would be distributed through an international scheme based on Brazil's ICMS ecológico (a successful intergovernmental fiscal transfer scheme) to compensate for land uses that generate a bundle global ecosystem services, such as reducing emissions from deforestation and forest degradation (REDD). Funds should also be invested in open source technologies that protect and provide global ecosystem services. Our recommendations may appear naïve in today's political climate, but global climate change and biodiversity loss are two of the most serious threats our civilization has ever faced, and people are beginning to wake up to this fact. Solving these problems without significant resources may prove impossible.

2. The Status and Nature of the Services

Ecosystem services are frequently defined as "the benefits people obtain from ecosystems" (TEEB, 2008). A more useful definition distinguishes between ecosystems as funds and stocks (Georgescu-Roegen, 1971). An ecosystem fund is a particular configuration of structural components (water, minerals, soil, plants, animals and so on) that generates a flux of services of value to humans and other species. The fund provides services at a given rate over time and is not physically transformed into the services it provides. Services cannot be stockpiled. In contrast, the structural components of ecosystems alternatively serve as stock-flow resources that can be used up at a rate we choose, are physically transformed into products, and can be stockpiled.

The waste absorption capacity for CO_2 (a service) and biodiversity (a critical component of ecosystem funds that generates a variety of services, hereafter referred to as a service) serve as excellent case studies for IPES schemes for three reasons: they are two of the most important global ecosystem fund-services and their adequate provision helps protect a number of other services (Balmford and Bond, 2005; IPCC, 2007a; Millennium Ecosystem Assessment, 2005; Stern, 2006; TEEB, 2008; Wilson, 2002); they are the focus of existing PES schemes (Landell-Mills and Porras, 2002; Pagiola et al., 2002; Wunder, 2007); and their physical characteristics are sufficiently different from each other so that schemes capable of providing them both can be generalized to other ecosystem fund-services.

Though fraught with uncertainty, climate models predict potentially catastrophic impacts, including the loss of up to 50% of biodiversity, if temperatures increase even 3 °C. With a doubling of CO_2 equivalent levels[1] (CO_2-e) over pre-industrial levels, the IPCC estimates a 77% chance of temperature rise exceeding 2 °C. Absent emission reductions, CO_2-e levels may double by 2035. We will need to reduce global emissions by 70% by 2050 and by 80% by 2100 if we hope to limit CO_2-e levels to a 62% increase (450 ppm) (IPCC, 2007d; Meinshausen, 2006; Stern, 2006). Even current atmospheric carbon stocks (about 390 ppm CO_2, or 430 ppm CO_2-e) put us at serious risk, and some leading scientist call for stabilizing CO_2 stocks at 350 ppm (Hansen et al., 2008)[2]. An equal per capita distribution of waste absorption capacity would require wealthy nations to eventually reduce their emission flows by at least 90% even if we ignore historic contributions to the atmospheric stock.

The impacts of biodiversity loss are even more uncertain, but potentially at least as severe (TEEB, 2008). Biodiversity is a complex multi-level concept, encompassing genetic diversity—the variability of genetic material within species; species diversity—the variability among and between species; and ecosystem diversity—the variety and complexity of communities of species (Clark and Downes, 1996). Abundant evidence suggests that biodiversity enhances both the productivity and stability of ecosystems, maintaining resilience in the presence of shocks and ensuring the continued provision of ecosystem services (Chapin et al., 1998; Gowdy, 1997; Naeem, 1998; Odum, 1989; Tilman and Downing, 1994; Worm et al., 2006). Biodiversity therefore acts like an insurance policy against catastrophic change, and climate change increases the value of biodiversity. Current rates of species loss are 100–1000 their pre human levels (Pimm et al., 1995). If we lose enough diversity, we risk catastrophic collapse of the ecosystem and with it almost all ecosystem services (Millennium Ecosystem Assessment, 2005; TEEB, 2008).

Both climate stability and biodiversity are essential to human well-being, and given their system-wide impacts, it seems unlikely that we can develop technological substitutes for the benefits they provide (Stern, 2006; TEEB, 2008). However, their very different characteristics as ecosystem services mean that different mechanisms will be required to ensure their continued provision.

Climate regulation is a perfect example of a pure global public good. The service is completely non-excludable; once available it is virtually impossible to prevent people from using it. It is also completely non-rival; one person's use of the service has no impact on the quantity of the service left for others to use. Conventional markets fail to directly provide pure public goods. However, waste absorption capacity is a rival good—when an ecosystem absorbs one country's CO_2 emissions, it has a reduced capacity to absorb someone else's. Waste absorption capacity becomes excludable when governments pass and enforce laws regulating waste emissions, which creates property rights where none existed previously. While climate change will have different impacts in different places, the spatial distribution of greenhouse gas (GHG) emissions does not matter. Such

[1] CO2 equivalent (CO_2-e) includes the impact of other greenhouse gasses converted into CO_2 equivalents.

[2] Note that the Stern Review uses CO_2-e, while Hansen et al. refer to CO_2, so the numbers are not directly comparable.

characteristics mean that market allocation of waste absorption capacity is in theory quite simple, though prone to free-riding when some countries refuse to regulate emissions.

The physical characteristics of biodiversity in contrast make it exceedingly difficult to provide through market mechanisms. Like climate stability, the benefits of biodiversity are inherently non-excludable, so that it is virtually impossible to develop a market mechanism through which only those who pay for conserving biodiversity benefit. There is thus an incentive for some nations and individuals to free-ride on the conservation efforts of others. Most of the benefits are also non-rival, so any mechanism that required payment to enjoy existing benefits would actually reduce the use and hence value of these benefits. The ecosystem structure that sustains biodiversity is often excludable and rival, and is already bought and sold in markets. However, even here private property rights are often poorly defined or poorly enforced and controlled by different institutions, confounding efforts to create effective markets. In addition, the benefits of biodiversity vary considerably across time and space, ignoring political boundaries. In contrast to reducing greenhouse gas emissions, where biodiversity conservation takes place has a profound impact on the level of benefits and their distribution, so that every conservation project must be evaluated separately, yet in many cases even experts lack the knowledge to perform accurate evaluations.

3. How Much Should we Dedicate to the Provision of Global Ecosystem Services? A Qualitative Assessment

While some biodiversity and some climate stability are essential, we do not know how much of both we should preserve. Economists argue that we should preserve or restore ecosystems as long as the marginal benefits of doing so exceed the marginal costs. The challenge lies in identifying, measuring and comparing the myriad costs and benefits involved. In complex ecological–economic systems, elements of this challenge include uncertainty and systemic ignorance regarding ecological outcomes and technological progress (Faber et al., 1998), potentially incommensurable values (Martinez-Alier et al., 1998), and the difficulties in comparing future and present values (Voinov and Farley, 2007).

In deciding how much to dedicate to mitigating climate change, economists have primarily used cost benefit analysis (CBA). Many of these studies claim that the net present value of vigorous mitigation efforts may be negative, and we should focus initially on low or no-cost mitigation efforts (e.g. Nordhaus, 2008), which could still reduce emissions by as much as 23% by 2020 in the USA (Creyts et al., 2007). Some economists even claim that because climate change primarily affects agriculture, which is only a small percentage of GNP in the wealthiest nations, it will have minimal impacts on our welfare (Beckerman, 1995; see Daly, 2000 for discussion; Schelling, 2007); the underlying assumption is that all resources have substitutes, even food. Other studies using lower discount rates find that the net present value of mitigation efforts are positive (Cline, 1992; Stern, 2006). The Stern Review (Stern, 2006), for example, concludes that without mitigation efforts, climate change by 2050 will reduce GNP by 20% compared to what it otherwise would have been, and argues we should spend about 1% of gross world product annually to mitigate this loss. However, the Stern Review assumes that even with unmitigated climate change, the economy will be more than twice as large in 2050 as it currently is (which we consider a highly unlikely assumption), and its authors thus ask the current generation to make sacrifices for much richer future generations.

Unfortunately, such CBA does not hold up well under scrutiny, as the Stern Review itself explains at considerable length. First, measuring all values from loss of human life to species extinction in the same unit (generally money) is morally and scientifically dubious (Ackerman and Heinzerling, 2004; Gowdy, 1997; Martinez-Alier et al., 1998; Vatn and Bromley, 1994). Second, the discount rate is a critical variable in CBAs, but there is considerable debate over the proper discount rate, or even whether a positive discount rate is appropriate at all when dealing with large systems and the distant future (Portney and Weyant, 1999; Voinov and Farley, 2007; Weitzman, 1998). Third, CBAs require that uncertain values be replaced with a “certainty equivalent” or that extensive sensitivity analysis be done, but in many cases we have no idea what future outcomes will be, much less their probability. Fourth, empirical studies have shown that CBAs of environmental regulations systematically overestimate the costs of compliance (Ackerman and Heinzerling, 2004; Harrington et al., 1999). Finally, all CBAs of climate change that we know of assume a background rate of continued economic growth, which may be impossible to sustain in the face of environmental degradation and without continued large scale use of fossil fuels (Deffeyes, 2003; Heinberg, 2003).

There is considerably less data on how much we should spend to deal with the global biodiversity crisis, as most studies focus only on individual ecosystems and species (Turner et al., 2007). Contingent valuation studies for non-use values suggest that global willingness to pay for protecting tropical forests ranges from $25–$1400/ha/year (Pearce, 2007), but these values are probably trivial compared to biodiversity's indirect use values in sustaining essential ecosystem services. James et al. (2001) calculate that $317 billion/year would be required to maintain global biodiversity and evolutionary potential, and Balmford et al. (2002) find that returns on the first $45 billion invested annually would be 100:1. Current expenditures are in the neighborhood of $10 billion annually (Pearce, 2007).

The most serious challenge to deciding how much we should pay to protect climate stability and global biodiversity is the level of uncertainty involved. Future outcomes depend on both evolutionary and technological change, which are unpredictable by their very nature (Faber et al., 1998). The global ecosystem is an extremely complex non-linear system with a sample size of one, and there may be time lags of decades to centuries before the full impacts of our activities are felt. At least some level of climate stability and biodiversity are essential to human survival, and substitution for the services they provide may be impossible. Services with such characteristics exhibit inelastic demand, and as their supply dwindles to critical levels, small changes in quantity will lead to enormous changes in marginal value. Take for example an ecosystem such as the Amazon rainforest, a mega-diverse region that helps regulate the global climate (Flannery, 2005). Studies suggest that if as little as 30% of the forest is cleared, it will no longer generate enough rainfall to sustain itself, and may convert into a savannah system. The resulting loss of ecosystem services could prove catastrophic (Nepstad et al., 2007; Salati, 1987; Salati and Vose, 1984). As we near this critical threshold, the marginal value of a forest hectare increases astronomically, and marginal valuation of benefits becomes increasingly inappropriate (Farley, 2008; Limburg et al., 2002; Pearce, 2007).

Estimating the opportunity costs of protecting these ecosystem services, as measured by reduced expenditures on other activities, is subject to much less uncertainty. We have real data on quality of life for historically lower levels of consumption. The Stern Review claims that it would require 1% of gross world product annually over the next 50–100 years to stabilize atmospheric carbon at 550 ppm, reducing the risk of exceeding a potentially catastrophic 3 °C climate change to 32%, according to IPCC models. Had we initiated such mitigation efforts last year, we would currently be enjoying our living standards from 4–5 months ago. The estimated costs of stabilizing at 450 ppm, where there is only a 6% chance of exceeding 3 °C climate change, range from an additional 0.31%–0.76% of gross world product (Stern, 2006), which would force us to accept our living standards from 8 months ago.

Recent studies have shown that economic growth is not required to reach full employment, reduce poverty and deficits, or achieve other important societal goals (Jackson, 2009; Victor, 2008). A growing number of economists argue that ecological sustainability and social justice actually requires degrowth (economic contraction) in the wealthier nations (Flipo and Schneider, 2008; Rijnhout and Schauer, 2009). The annual increment in per capita economic output from the World's wealthiest nations (the European Union, the United States, Japan, Canada and Australia) could provide some $800 billion (2% of $40 trillion) annually (IMF, 2009) for addressing climate change and biodiversity loss, much of which could fund IPES. Accepting degrowth in consumption could generate substantially more revenue. While historically the poor have suffered the most from unplanned economic contractions, a planned contraction and reallocation of expenditures can avoid such outcomes (Victor, 2008).

4. Assessing Existing Global Institutions

Global public goods generated by complex systems with diffused costs and benefits, biodiversity, and climate stability combine "all the factors that make it hard to construct successful foreign policy" (Victor, 2004). As is obvious from their continuing degradation, existing mechanisms for providing these global public goods are indeed inadequate.

Effective mechanisms should follow the 10 principles laid out in the Heredia Declaration on payments for ecosystem services, which are HP1) measurement of services provided; HP2) bundling of services; HP3) matching the scale of institutions to services; HP4) establishing property rights, common or private; HP5) just distribution; HP6) sustainable funding; HP7) adaptive management; HP8) education to achieve political will; HP9) broad stakeholder participation; and HP10) policy coherence (see Farley and Costanza, 2010-this issue for details).

Mechanisms should also allow micro-flexibility in achieving macro level goals (Daly and Farley, 2004). Macro level goals should be determined by the best available science concerning ecological thresholds (e.g. biodiversity required to sustain critical ecosystem services and evolutionary potential, the ecological absorption capacity for carbon dioxide) weighted by global societal attitudes towards risk and our ethical obligations to future generations (see Rockstrom et al., 2009 for estimates of relevant thresholds). For both biodiversity and climate stability, centralized institutions can gather most available knowledge, serve as a forum for discussing relevant values, and make the best educated guesses concerning acceptable levels of carbon emissions and biodiversity loss, as has been attempted with the Intergovernmental Panel on Climate Change (IPCC), the Convention on Biological Diversity (CBD), and the Millennium Ecosystem Assessment (MEA). However, it is considerably more difficult for any global institution to centralize knowledge about the local costs and benefits of reducing carbon emissions, increasing carbon capture, and sustaining biodiversity, which can vary dramatically across short distances within the same ecosystem. An appropriate mechanism should, like markets, be able to use "knowledge which is not given to anyone in its totality" (Hayek, 1945, p. 520).

4.1. Carbon

Climate change can be addressed through combinations of adaptation and mitigation, but only the latter seeks to provide global ecosystem services. Mitigation requires either reducing carbon emissions or increasing absorption capacity. The world's landmark institution for addressing climate change, the Kyoto Protocol to the UNFCCC, employs both approaches, taking advantage of the rival nature of the waste absorption capacity for CO_2 and our ability to create excludable property rights to waste emissions.

Specifically, Kyoto negotiates macro level caps on carbon emissions (assigned amounts) in the Annex I countries (industrialized and transition countries obliged to reduce emissions) then allows three micro-flexibility mechanisms for meeting these caps. The Clean Development Mechanism (CDM) allows Annex II (most developed) countries to earn tradable carbon credits (certified emission reductions or CERs) by funding abatement projects promoting "sustainable development" in non-Annex I (less developed) countries that otherwise have no emissions reduction commitments. Joint Implementation (JI) basically allows Annex II countries to do the same for transition countries, earning in this case emission reduction units (ERUs). CDM and JI activities can either decrease sources of carbon or increase sinks to offset emissions in Annex II countries, but must meet the additionality requirement by providing net reductions relative to the emissions level expected in the absence of a particular project's implementation. Emissions trading, launched in 2008 allows those Annex I countries that exceed their emissions reductions target to trade permits (assigned amount units or AAUs) with those who fall short. CERs, ERUs and AAUs are all standardized to one ton of CO_2 equivalent (UNFCCC, 1998).

Within their borders, Annex I countries are free to meet their caps as they see fit, but by far the dominant mechanism to date is cap and trade, mirroring Kyoto's architecture. The EU's Emissions Trading System (EU-ETS), launched in 2005, is the world's largest carbon trading market, covering nearly 50% of EU emissions. In the trial phase (2005–2007) most permit allocations (EUAs) were given away to polluting firms, and actually exceeded business as usual emissions. After this was revealed in April 2006, prices plunged, approaching zero by December 2007 (Alberola et al., 2008). In Phase II (2008–2012) EUA prices have fluctuated widely, declining by 1/2 between October 2008 and December 2009 as the recession led many firms to sell off the EUAs they had received for free. Nonetheless, the EUA market was worth nearly $92 billion in 2008. Phase III (2013–2020) will aim to cut emissions to 20% below 2005 levels, falling short of the 25–40% reductions recommended by the IPCC in order to stabilize atmospheric emissions at 450 ppm. At least half of EUAs will be auctioned off beginning in 2013, gradually ramping up to 70–80% by 2020 (Capoor and Ambrosi, 2009).

While the emissions trading of the Kyoto Protocol and EU-ETS is in principle cost effective, the other flexibility mechanisms may not be, and may undermine macro level caps. Through 2007 some 30% of CDM projects were based on oxidation of HFC-23, a byproduct of producing HCFCs, and costs were so low that firms earned more from selling CERs than from producing the HCFCs themselves. Simply subsidizing the costs of oxidization instead of using the CDM would have saved €4.6 billion to spend on other forms of climate protection (Wara, 2007). Ozone experts argue that the direct regulations of the Montreal Protocol are far more efficient than market mechanisms at reducing emissions, and should be extended to include green house refrigerants (Tollefson, 2009). Proving additionality is challenging, as offsets "are an imaginary commodity created by deducting what you hope happens from what you guess would have happened."(Welch, 2007) Additionality may even create perverse incentives for countries to lower environmental standards, so that more projects count as additional (Mukerjee, 2009). Rapidly cycling biological carbon cannot meaningfully offset geologic carbon that would otherwise remain sequestered for millions of years, and there is even evidence that some offset projects increase carbon emissions through soil oxidation (Lohman, 2006). Offsets are intended to reduce the cost of meeting caps, which also reduces incentives to develop alternatives to fossil fuels. Though two fifths or more of CDM projects may actually involve no net reductions (Mukerjee, 2009), when we exclude them the EU-ETS failed to reduce emissions at all through 2009 (Gilbertson and Reyes, 2009). Finally, many CDM projects may have negative impacts on the poor (Lohman, 2006), though there is hope that the agreement at COP 15 in Copenhagen to allow reducing emissions from deforestation and forest degradation (REDD) may aid the poor (Coomes et al., 2008) and protect other ecosystem services as well.

Other shortcomings of the Kyoto Protocol from the perspective of IPES include the lack of participation by some of the worst emitters, the extensive influence of the business sector on emission levels, and the failure to bundle other ecosystem services with carbon sequestration. The need for the IPCC reports to achieve some degree of consensus across all participating nations may limit their ability to educate politicians and the general population on the importance of climate change.

4.2. Biodiversity

Given the unavoidable public good nature of the problem, "it is no surprise that private purchasers of biodiversity's benefits are hard to come by, which explains why there are so few true markets for biodiversity" (Salzman, 2005, p. 883). Non-market institutions such as government will almost certainly be required to solve the problem, but international institutions at the scale of the problem have just begun to emerge. Owing to space limitations, we focus here only on the Global Environmental Facility (GEF) which is the financing mechanism for the Convention on Biological Diversity (CBD) and hence the main source of multilateral financing for biodiversity preservation and conservation.

The Global Environmental Facility became operational in 1992, and serves as the financing mechanism for both the implementation of the CBD and UNFCCC. The GEF provides "a mechanism for international cooperation for the purpose of providing new and additional grant and concessional funding to meet the agreed *incremental costs* of measures to achieve agreed environmental benefits" (UNDP-GEF, 1998). Four out of 15 operational programs focus exclusively on biodiversity, following CBD guidelines, which emphasize conservation of biodiversity, sustainable use of its components, and fair and equitable sharing of benefits arising from the use of genetic resources. Funding is disbursed on a project-by-project basis, each requiring a grant proposal. Proposals are submitted directly to the UNDP, UNEP, or the World Bank, which are the implementing and executing agencies. The GEF explicitly strives to foster market mechanisms for biodiversity goods and services, including PES.

The GEF is funded by voluntary donations from wealthy nations, with no guarantee of sustainability. It disburses resources to countries based on global environmental priorities as measured by the climate change and biodiversity components of a GEF Benefits Index, and by country-level performance that ranks countries by their ability to meet GEF biodiversity objectives. Unfortunately, only one of 15 operational programs targets projects that bundle at least two ecosystem services. Though the GEF pushes for sustainable financing of protected area systems at the national level, disbursement on a project-by-project basis fails to assure funding beyond the typical five to seven year project cycle. The operational principle of funding only incremental costs attempts to match institutions to the scale of the problem. However, the difficulties in determining incremental costs are akin to those of determining additionality, as described above. In practice, the GEF reputedly calculates the difference between a total project budget and the national share of that budget, and declares that sum to be equal to incremental costs.

The bi-annual Conferences of the Parties (COPs) for the CBD facilitates adaptive management at the institutional level, but the short-term project time horizons offer little opportunity for adaptive management within actual projects. The COPs also seek to improve policy coherence and are currently examining proposals for removing or mitigating perverse incentives that threaten biodiversity.

The GEF makes abundant educational material available on the Web, carries out monitoring and evaluation of all its projects, and discloses all non-confidential information. Participation, flexibility and cost effectiveness are all operational principles of the GEF, but its centralized nature does little to facilitate them (GEF, 2004; UNDP-GEF, 1998).

Perhaps most problematic, potential recipients must submit project proposals to a centralized bureaucracy that decides which projects are best then funds them for a fixed period of time. Proposal writing takes considerable effort, and limits funding to those with writing skills. Reviewing proposals also requires effort, and centralized decision makers inevitably lack the knowledge of local circumstances that would be required to make the best decisions, limiting opportunities for micro-flexibility. Once money is disbursed, there is no guarantee that projects will succeed, in spite of expensive monitoring and evaluation. The GEF operates as a central authority with centralized knowledge, and in many ways is the antithesis of a market mechanism.

5. Possibilities for New IPES Schemes

If we are to build a sustainable future for humanity, we must develop mechanisms that will ensure the provision of critical global ecosystem services which existing international mechanisms have failed to adequately protect. We require both far more resources and better mechanisms. However, given the urgency of the problem, we must work with what we have and improve as we go.

Appropriate mechanisms must collect and disburse funds effectively and ratchet funding upwards or downwards as needed to adequately address the problem. Collecting funds confronts a global collective action problem. Auctioning off carbon caps or taxing emissions can simultaneously help stabilize the global climate while providing funds for global biodiversity PES schemes. Concerning disbursement, there is still considerable debate at a national level whether regulations are superior to market mechanisms, and whether market mechanisms should be based on property rights, incentives, or disincentives (Coase, 1988; Gustafsson, 1998). The debate is simpler at the global level: no authorities currently exist capable of imposing regulations or disincentives and many countries feel threatened by outright land purchases, which forces us to rely on incentive mechanisms. We propose adapting an existing policy used in several Brazilian states, known as the "ecological value added tax", to the global level. Biodiversity and carbon sequestration projects should complement national projects that provide other ecosystem services. Sequestration projects should not be in the form of offsets, which substitute for emissions reductions, but rather should complement such reductions. We also propose an indirect approach to global PES based on the more efficient production and dissemination of technological solutions, which requires a fundamental rethinking of global intellectual property rights.

5.1. Finance: Collecting Adequate Resources while Reducing Carbon Emissions

Sustainable funding at adequate levels is a prerequisite for any effective global system of payments for ecosystem services. Mechanisms should be automatic, not voluntary. Suitable mechanisms for financing global public goods include charges for the global commons (Stiglitz, 1999), international taxation, a Tobin tax on financial transactions (Bezanson and Mendez, 1995), and the re-targeting of an estimated $950–1450 billion dollars annually in environmentally perverse subsidies (James et al., 2001). An ideal financing mechanism should meet three key criteria. First, the marginal payment from each contributor should at least be proportional to benefits received or harm done. Second, there should be a feedback loop through which revenue collected increases or decreases along with threats to the services in question. Third, transaction costs should be minimized, which is more likely to happen if the collection system piggy backs on existing institutions or mechanisms.

A charge on global carbon sequestration capacity via taxes or cap and auction schemes not only helps address climate change, but could also generate revenue for the provision of other global public goods (Cooper, 2002). Proportionality of payments is obvious for climate stability, but also holds for biodiversity. The major threats to biodiversity loss include climate change, habitat loss and degradation, pollution and unsustainable harvest levels (Millennium Ecosystem Assessment, 2005). Energy (which in modern society means fossil fuels) is required to do work and work is required to convert habitats to other uses and to harvest species. Fossil fuels drive climate change and are a major source of pollution. Carbon charges would therefore also collect revenue from those who pose the greatest threats to biodiversity.

Global carbon taxes provide a built-in feedback mechanism for funding biodiversity—revenues rise and fall with fossil fuel use, so more resources for PES schemes become available as threats increase. In cap and auction schemes without offsets, however, supply is determined by society, not by the market. While the CDM mechanism theoretically allows the supply of waste absorption capacity to respond to price increases, it is fraught with difficulties as discussed above. The necessary feedback loop must instead be achieved through the process of adaptive management, for example through a periodic Conference of the Parties, which adjusts the socially determined supply in response to new information. As demand for energy is inelastic, demand for emissions permits would be as well, and generating more revenue would require reducing caps. However, cap and auction provides a better feedback mechanism than taxes for climate stability, as prices can adjust to caps determined by ecological criteria much more readily than ecosystems can adjust to emission quantities determined by prices (Daly, 1997). If the cap were set to reach the waste absorption capacity for carbon dioxide (about 20% of current emissions (IPCC, 2007d)) over a given time span, , it would not need to be changed, while taxes targeting the same emissions level would need to be readjusted constantly. A number of economists have argued that taxes produce less volatile prices (e.g. Kahn and Franceschi, 2006), but variations in supply contribute substantially to the price volatility of fossil fuels (and other resources exhibiting inelastic demand), and quotas should reduce this source of volatility. On balance, we believe that cap and auction is preferable to taxes, but either is appropriate.

How much money could such schemes generate? Estimates vary wildly, as we cannot predict new cost-saving technologies. RAND corporation economists estimate that a \$30/ton carbon dioxide tax (~\$8.70/ton carbon) would reduce emissions by 20% and generate over \$150 billion dollars per year in the US alone (Crane and Bartis, 2007). Though the EU-ETS scheme may have actually given out more emission permits than required, credit permits markets were nonetheless worth nearly \$125 billion in 2008 (Capoor and Ambrosi, 2009), suggesting that the RAND study may underestimate potential revenues. We favor caps that reduce emissions by at least 25–40% over 1990 levels by 2025, as called for by the IPCC in targeting 450 ppm atmospheric CO_2 (IPCC, 2007b). Nordhaus claims this target would require steadily increasing taxes beginning at \$300/ton (Nordhaus, 2007), and auctioned permits should cost the same, generating adequate funding for a meaningful global IPES scheme.

A sticky issue with negotiating such a cap and auction scheme is the refusal of the US and some other wealthy countries to make meaningful emissions reductions unless major polluters such as India and China do so. Developing countries argue that they were not responsible for current atmospheric stocks, and therefore should not be forced to curtail current emissions to address the problem. A compromise is to negotiate a cap and auction system for the relatively few countries responsible for 90% of global emissions, then allow the developing countries to spend auction revenue on their own development needs.

Unfortunately, participation and complete property rights will remain a problem with this and other strategies as long as countries continue to prioritize economic growth over ecological life support functions. The issue is really one of education and politics: neither the general public nor decision makers appear to be well-informed concerning the relative contributions of global ecosystem services and economic growth to our well-being.

5.2. Two Proposals for Alternative Global PES Schemes

Funding a PES scheme is only half the challenge. An efficient PES system for global public goods also requires an efficient disbursement mechanism. Our assessment of the GEF found that while it has certain strengths, centralized decision-making allows little micro-flexibility in pursuit of macro goals, and creates high transaction, monitoring and evaluation costs, so that it is unlikely to be cost effective. The GEF is also ill suited for countries where property rights are poorly defined. We need instead a system through which appropriate incentives to achieve global goals are supplied at the global level, but decisions are made at the local level. The system should also be flexible enough to cope with poorly defined private property rights and the different legal, economic and social institutions around the world. Transaction costs should be minimized, and national sovereignty must be respected.

5.2.1. Brazil's ICMS Ecológico Adapted to a Global Scale

An intergovernmental fiscal transfer policy dubbed the ICMS Ecológico (ICMS-E), used in some Brazilian states to pay for ecosystem services could be adapted to the global level and should offer substantial improvements over existing mechanisms. Brazilian states capture most of their revenue from sales taxes, and by law must return 25% to municipalities. The states are allowed to determine the criteria by which 25% of these funds (i.e. 6.75% of the total) are returned to the municipalities. In 1991, the state of Parana implemented a law that awarded 5% of ICMS revenue to municipalities in proportion to their protection of watersheds and conservation areas. The initial goal of this policy was to compensate municipalities for the opportunity costs of conservation areas and for protecting watersheds that benefited other municipalities, but the way in which the law was implemented created significant incentives for the creation of new protected areas. Explicit objectives of the policy now include increasing the number and area of protected areas; enhancing the regularization, planning, implementation and sustainability of protected areas; providing incentives for the construction of ecological corridors connecting habitat fragments; stimulating the adoption, development and consolidation of state and municipal institutions relevant to biodiversity conservation; and fiscal justice for environmental conservation. The net result is an incentive to maintain and expand land uses that provide critical ecosystem services through the provision of natural capital (Grieg-Gran, 2000; Loureiro, 2002; May et al., 2002; Ring, 2008).

In Parana, there are two basic criteria for disbursing money for conservation areas. First is the quantitative coefficient of biodiversity conservation, which is simply the percentage of municipal land area under conservation corrected by a multiplier that characterizes the level of restriction on use (e.g. biological reserve, park and so on). Payments to municipalities are even provided for federal and private protected areas. Second is a qualitative dimension that assesses the physical and biological quality of the conservation unit, the quality of water resources in and around the unit, the extent to which the unit is representative of ecosystems in the region, the quality of planning, implementation, maintenance and management, infrastructure, equipment, legitimacy of the unit in the community, and so on. Municipalities are under no obligation to create and improve protected areas, but are awarded to the extent they meet these criteria relative to other municipalities. As only a fixed pool of money is available in any given year, the municipalities in effect compete with each other to receive the money (Loureiro, 2002).

So far, the model appears to be quite successful and cost effective. In Parana, total conservation units increased by over 160% between 1992 and 2007, while municipal protected areas, those most directly affected by the policy, have increased by over 2500% (Denardin et al., 2008). Transaction costs have been very low: in the first 4 years following implementation, approximately US\$30 million dollars were redistributed at an incremental administrative cost of only \$30 thousand (Vogel, 1997).

Conceptually, it would be very simple to adapt the model to the global scale with a global institution financed by carbon charges allocating its annual budget to countries, states or even municipalities (hereafter referred to as providers) in proportion to the quantity and quality of ecosystem services they provide. In practice however, there would be significant problems to overcome.

Lump sum payments to providers who meet specified criteria regardless of how or why they do so eliminates concerns over leakage and additionality by forcing the wealthy countries to pay for all benefits received, including those they would have received anyway by free-riding on existing provision. Conditional lump sum transfers are payments for services currently provided. However, such payments could be used to fund projects that ultimately degrade ecosystem services if providers believe these would be eventually prove more lucrative than payments. An alternative is to earmark payments for additional investments in ecosystem services. However, earmarking of funds requires both monitoring of use and verification of outcomes, which are expensive, intrusive and, given the fungibility of money, quite difficult. Theoretical models indicate that earmarks are appropriate for activities that increase ecosystem services, while lump sum transfers are better for protecting existing provision, suggesting a hybrid approach (Dur and Staal, 2008; Kumar and Managi, 2009). Whether REDD should be considered existing provision and funded through lump sum transfers, or as an increase in services, is subject to debate.

Another option would be to award providers for improvements over baseline conditions, for services that they would not otherwise have provided. This would confront the problems of setting baselines and proving additionality. Furthermore, those countries that have carefully protected their ecosystems would have no new incentives to continue doing so, and might even begin degrading ecosystems simply to become eligible for future compensation (Pagiola et al., 2004).

Yet another challenge is determining actual reward criteria in addition to monitoring, reporting and verification. Criteria should be determined at the global level by appropriate experts in biodiversity, ecosystem services, landscape ecology and so on, and would presumably be a weighted index of area, quality and legal protection. Measurement must balance accuracy with cost effectiveness and respect for sovereignty. Remote sensing data and techniques are already capable of identifying species' habitats, predicting species richness and detecting natural and anthropogenic change from the landscape to global levels. While still subject to substantial error, remote sensing is cost effective, steadily improving (Kerr and Ostrovsky, 2003) and minimally intrusive on national sovereignty. As has been the case for the ICMS-E, Criteria can be simple to begin with but steadily improved upon as knowledge and expertise increases (Grieg-Gran, 2000).

Whatever approach is taken, payments should target bundled services. While targeting forest conservation based solely on carbon sequestration also improves biodiversity conservation, targeting both biodiversity protection and carbon sequestration simultaneously may allow doubling the former at a cost of 4–8% in the latter (Venter et al., 2009). Currently, carbon sequestration and forest protection (REDD) projects are considered offsets that substitute for emissions reductions elsewhere, and focus almost entirely on carbon. Instead, such projects should be funded as complements to binding caps to help stabilize atmospheric CO_2 concentrations below 450 ppm while simultaneously providing biodiversity habitat and other services. Local and national governments should also strive to bundle important local services into IPES schemes.

In spite of significant challenges to be overcome, the proposed policy has important advantages. It operates on a political scale where property rights are well enforced, eliminating the problems posed by insecure land tenure. Perhaps most important, the policy allows micro-flexibility in the pursuit of macro goals while utilizing institutions at the scale of the problem. Macro goals are set at the global level along with appropriate criteria measuring the extent to which they are achieved. Providers have different cultures, legal institutions and opportunity costs of preserving biodiversity, and the mechanism allows them to act on local knowledge not available to any centralized authority and choose appropriate national or local policies for conserving ecosystem services, helping to ensure policy coherence. Just as firms copy industry innovators in conventional markets, we can expect providers to copy the most cost effective and successful approaches. Also like conventional markets, providers would compete for a pool of money, which would provide constant incentives for greater efficiencies through innovation.

5.2.2. Indirect Payments for Ecosystem Services: Open Source Information

Failure to eventually stabilize atmospheric carbon would almost certainly impose unacceptably high costs on society. However, stabilization requires net emissions reductions of 80% or more, which also threatens unacceptable costs with current technologies (IPCC, 2007c; Stern, 2006). We confront the possibility of conflicting thresholds–a marginal cost curve (supply) and marginal benefit curve (demand) for CO_2 emissions that do not intersect–and no economically optimal solution to the climate change problem with existing technologies, as depicted in Fig. 1.

While little can be done to change ecological costs of emissions, the invention, innovation and diffusion of new technologies can help

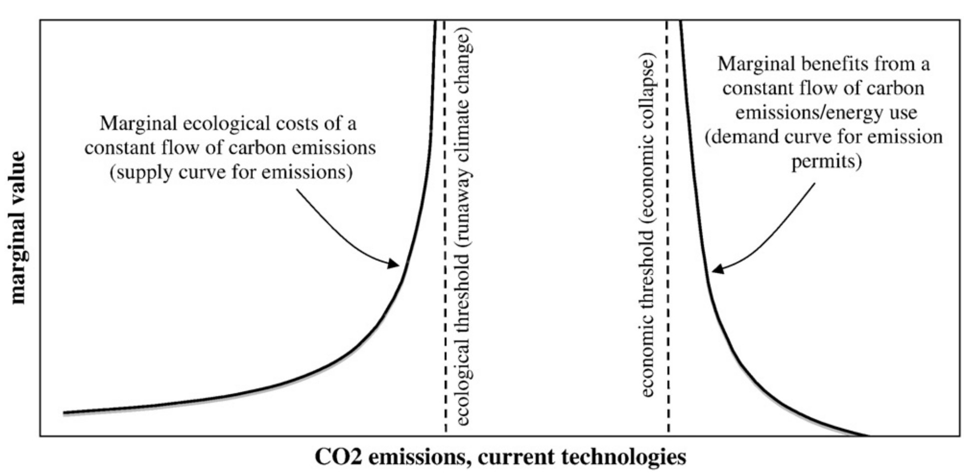

Fig. 1. Conflicting thresholds for CO_2 emissions under current technologies, where supply and demand curves fail to intersect. Emissions levels in the absence of regulation correspond to marginal value of emission permits equal to zero.

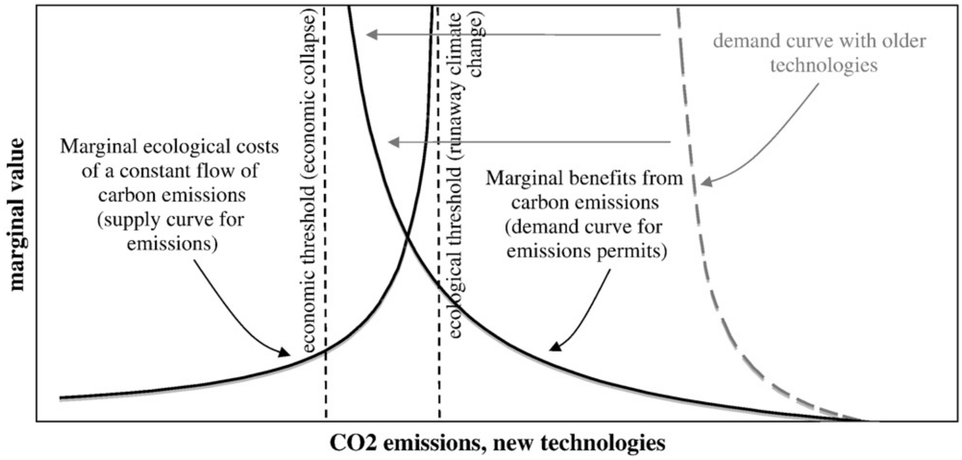

Fig. 2. Technological innovation can shift the demand curve for carbon emissions to the left and make it more elastic.

reduce the economic costs of reducing emissions, shifting the marginal benefit curve from emissions to the left and making it more elastic, as depicted in Fig. 2. The lower the level of stabilization we aim for, the more rapidly we require new technologies.

While there is little doubt that putting a positive price on carbon emissions will create incentives for the private sector to develop low carbon energy technologies, there are a number of reasons why market forces alone are inappropriate for this task (Foxon, 2003; Stern, 2006). Information has characteristics of a public good. Even patented information is not completely excludable. Once a technology is developed by one firm at high cost, other firms can cheaply copy it. The result is under-investment by the private sector in new technologies (Arrow, 1962). Information is also non-rival, and hence not scarce in an economic sense. The marginal cost of an additional user, which is also the efficient price, is virtually zero. A positive price for information creates artificial scarcity, reducing both use and economic surplus, but at the efficient price there is little market incentive to produce it (Daly and Farley, 2004). Intellectual property rights (required for positive prices) replace one market failure with another. Energy technologies are often risky and characterized by economies of scale, leading to investments in incremental rather than radical change (Stern, 2006). The basic problem is that private rates of return to R&D in energy are lower than public rates of return, resulting in under-investment from the private sector. Empirically, private sector R&D in the energy sector is low relative to other industries, and has declined significantly since the 1980's (Alic et al., 2003; Stern, 2006).

One commonly proposed policy for increasing private sector R&D is to strengthen intellectual property rights (IPRs) so that firms can capture higher returns on their investments. However, "green" energy technologies will only mitigate climate change if widely adopted, and the monopoly prices enabled by IPRs reduce use. Technology in general and energy technologies in particular are cumulative, and if patents prevent access to existing technologies, it can slow the development of new ones (Foxon, 2003; Heller, 1998; Scotchmer, 1991). Private sector scientists competing to patent new technologies fail to share knowledge, threatening excessive duplication of research.

Another common policy approach supported by most energy studies is to lower the costs of R&D, typically through publicly supported R&D. Currently, the public sector accounts for some 2/3 of energy sector R&D, but total public investments have also plunged since the 1980's (Doornbosch and Upton, 2006). The Stern Review calls for doubling global public sector R&D for energy to around \$20 billion per year, in pursuit of a diverse portfolio of new technologies, and suggests international cooperation to avoid free-riding.

While public sector energy R&D must increase, and international cooperation is important, it is in one sense impossible to free-ride on technologies that protect or provide global ecosystem services (GES), since the more people who use such technologies, the greater the benefits to all. Echoing Stiglitz' (1999) call for managing information as a global public good, society should pay for technologies that provide and protect GES by auctioning off the waste absorption capacity for CO_2 in the wealthy countries, then make them freely available to all. A global research consortium should determine appropriate technologies for alternative energy, agroecology, green chemistry, industrial ecology and so on in collaboration with those who would use them. These new technologies should be copylefted, meaning that they are freely available for anyone to use as long as derivative products are available on the same terms (Bollier, 2002). The global patent system is a descendant of the Bretton Woods institutions, which were designed to facilitate the production and dissemination of market goods in response to economic crisis. We now need global institutions to facilitate the production and dissemination of global ecosystem services and other public goods, in response to our ecological crises (Beddoe et al., 2009).

6. Conclusions

With the loss of global ecosystem services such as climate stability, biodiversity, screening from ultraviolet radiation and so on, humans may be facing the greatest threat to their well-being in recorded history. Though there is evidence that political will to address the problem is beginning to emerge, it will do little good without tested and effective policies. Unfortunately few policies have undergone rigorous evaluation for effectiveness, and such evaluation is desperately needed. The only way to know for sure if a policy works is to test it; "management actions should be viewed as experiments that can improve knowledge of social–ecological dynamics if the outcome is monitored and appropriately analyzed" (Carpenter and Folke, 2006). Given time constraints, we do not have time to try out dozens of policies sequentially to see which works best. In the face of potentially irreversible but highly uncertain biophysical limits, we need to act immediately. Institutions concerned with global environmental problems should fund large scale, carefully designed randomized experiments that compare several promising global PES mechanisms, including those described in this paper. We must implement the best of these policies on a broad scale, and continue to improve them through adaptive management.

Acknowledgment

We would like to thank the Blue Moon Fund for the funding necessary to carry out this research, and reviewers Peter May and Irene Ring for their numerous helpful comments.

References

Ackerman, F., Heinzerling, L., 2004. Priceless: On Knowing the Price of Everything and the Value of Nothing. The New Press, New York.
Alberola, E., Chevallier, J., ChËze, B., 2008. Price drivers and structural breaks in European carbon prices 2005–2007. Energy Policy 36, 787–797.
Alic, J., Mowery, D., Rubin, E., 2003. U.S. Technology and Innovation Policies: Lessons for Climate Change. Pew Center on Global Climate Change, Washington, DC.
Arrow, K., 1962. Economic welfare and the allocation of resources for invention. In: Nelson, R. (Ed.), The Rate and Direction of Inventive Activity. Princeton University Press, Princeton, pp. 609–625.
Balmford, A., Bond, W., 2005. Trends in the state of nature and their implications for human well-being. Ecology Letters 8, 1218–1234.
Balmford, A., Whitten, T., 2003. Who should pay for tropical conservation, and how could the costs be met? Oryx 37, 238–250.
Balmford, A., Bruner, A., Cooper, P., Costanza, R., Farber, S., Green, R.E., Jenkins, M., Jefferiss, P., Jessamy, V., Madden, J., Munro, K., Myers, N., Naeem, S., Paavola, J., Rayment, M., Rosendo, S., Roughgarden, J., Trumper, K., Turner, R.K., 2002. Economic reasons for conserving wild nature. Science 297, 950–953.
Beckerman, W., 1995. Small Is Stupid: Blowing the Whistle on the Greens. Duckworth, London.
Beddoe, R., Costanza, R., Farley, J., Garza, E., Kent, J., Kubiszewski, I., Martinez, L., McCowen, T., Murphy, K., Myers, N., Ogden, Z., Stapleton, K., Woodward, J., 2009. Overcoming systemic roadblocks to sustainability: the evolutionary redesign of worldviews, institutions and technologies. Proceedings of the National Academy of Sciences 106, 2483–2489.
Bezanson, K., Mendez, R., 1995. Alternative funding — looking beyond the nation-state. Futures 27, 223–229.
Bollier, D., 2002. Silent Theft: The Private Plunder of our Common Wealth. Routledge, New York.
Capoor, K., Ambrosi, P., 2009. State and Trends of the Carbon Market 2009. World Bank, Washington DC.
Carpenter, S.R., Folke, C., 2006. Ecology for transformation. Trends in Ecology & Evolution 21, 309–315.
Chapin III, F.S., Sala, E., Burke, I.C., Grime, J.P., Hooper, D.U., Lauenroth, W.K., Lombard, A., Mooney, H.A., Mosier, A.R., Naeem, S., Pacala, S.W., Roy, J., Steffen, W.L., Tilman, D., 1998. Ecosystem consequences of changing biodiversity. Bioscience 48, 45–52.
Clark, D., Downes, C., 1996. Economic incentives and biodiversity conservation in the United States. Oregon Journal of Environmental Law and Litigation 11, 9–90.
Cline, W.R., 1992. The Greenhouse Effect: Global Economic Consequences. Institute for International Economics, Washington, DC.
Coase, R., 1988. The Firm, the Market and the Law. University of Chicago Press, Chicago.
Coomes, O.T., Grimard, F., Potvin, C., Sima, P., 2008. The fate of the tropical forest: carbon or cattle? Ecological Economics 65, 207–212.
Cooper, R.N., 2002. The double dividend of emissions taxes: greenhouse gas reductions and revenue. In: Kaul, I., LeGoulven, K., Schnupf, M. (Eds.), Financing Global Public Goods: New Tools for New Challenges: A policy dialogue. United Nations Development Program, New York.
Crane, K., Bartis, J.T., 2007. On Carbon Dioxide, A Better Alternative. Washington Post, Washington, DC. November 29.
Creyts, J., Derkach, A., Nyquist, S., Ostrowski, K., Stephenson, J., 2007. Reducing U.S. Greenhouse Gas Emissions: How Much at What Cost?. Mckinsey & Company. Online: http://mckinsey.com/clientservice/ccsi/pdf/US_ghg_final_report.pdf.
Daly, H.E., 1997. Beyond Growth: The Economics of Sustainable Development. Beacon Press, Boston.
Daly, H., 2000. When smart people make dumb mistakes. Ecological Economics 34, 1–3.
Daly, H., Farley, J., 2004. Ecological Economics: Principles and Applications. Island Press, Washington, DC.
Deffeyes, K.S., 2003. Hubbert's Peak: The Impending World Oil Shortage. Princeton University Press, Princeton.
Denardin, V.F., Loureiro, W., Sulzbach, M.T., 2008. Distribuição de benefícios ecossistêmicos: o caso do ICMS ecológico no litoral paranaense. REDES, Santa Cruz do Sul 13, 184–198.
Doornbosch, R., Upton, S., 2006. Do we have the right R&D priorities and programmes to support the energy technologies of the future? OECD Round Table on Sustainable Development, Paris.
Dur, R., Staal, K., 2008. Local public good provision, municipal consolidation, and national transfers. Regional Science and Urban Economics 38, 160–173.
Faber, M.M., Proops, J.L., Manstetten, R., 1998. Evolution, Time, Production and the Environment. Springer-Verlag, New York.
Farley, J., 1999. "Optimal" deforestation in the Brazilian Amazon; theory and policy: the local, national, international and intergenerational viewpoints. Agricultural, Resource and Managerial Economics. Cornell University, Ithaca, NY.
Farley, J., 2008. The role of prices in conserving critical natural capital. Conservation Biology 22, 1399–1408.
Farley, J., Costanza, R., 2010. Payments for Ecosystem Services: From the local to the global. Ecological Economics 69, 2060–2068 (this issue).
Farley, J., Gaddis, E., Rees, W., VanDis, K., 2007. Our global footprint: managing global public goods. In: Aronson, J., Milton, S., Blignaut, J. (Eds.), Restoring Natural Capital: Science. Business and Practice. Island Press, Washington, DC, pp. 275–285.
Ferraro, P.J., 2001. Global habitat protection: limitations of development interventions and a role for conservation performance payments. Conservation Biology 15, 990–1000.
Ferraro, P.J., Kiss, A., 2002. Direct payments to conserve biodiversity. Science 298, 1718–1719.
Ferraro, P.J., Simpson, R.D., 2002. The cost-effectiveness of conservation payments. Land Economics 78, 339–353.
Flannery, T., 2005. The Weather Makers: Our Changing Climate and What it Means for Life on Earth. Penguin Books, London.
Flipo, F., Schneider, F. (Eds.), 2008. Proceedings of the First International Conference on Economic De-Growth for Ecological Sustainability and Social Equity, Paris, 18–19 April 2008. Online: http://events.it-sudparis.eu/degrowthconference/en/.
Foxon, T.J., 2003. Inducing Innovation for a Low-Carbon Future: Drivers, Barriers and Policies. The Carbon Trust, London.
GEF, 2004. Instrument for the Establishment of the Restructured Environmental Facility. United Nations Development Program, New York.
Georgescu-Roegen, N., 1971. The Entropy Law and the Economic Process. Harvard University Press, Cambridge, MA.
Gilbertson, T., Reyes, O., 2009. Carbon Trading: How it Works and Why it Fails. Dag Hammarskjöld Foundation, Uppsala.
Gowdy, J., 1997. The Value of Biodiversity: Markets, Society and Ecosystems. Land Economics 25–41.
Grieg-Gran, M., 2000. Fiscal incentives for biodiversity conservation: the ICMS Ecologico in Brazil. Discussion Paper 00-01. International Institute for Environment and Development, London.
Gustafsson, B., 1998. Scope and limits of the market mechanism in environmental management. Ecological Economics 24, 259–274.
Hansen, J., Sato, M., Kharecha, P., Beerling, D., Berner, R., Masson-Delmotte, V., Pagani, M., Raymo, M., Royer, D.L., Zachos, J.C., 2008. Target atmospheric CO_2: where should humanity aim? The Open Atmospheric Science Journal 2, 217–231.
Harrington, W., Morgenstern, R.D., Nelson, P., 1999. On the accuracy of regulatory cost estimates. Discussion Paper 99-18. Resources for the Future, Washington, DC.
Hayek, F., 1945. The price system as a mechanism for using knowledge. American Economic Review 35, 519–530.
Heinberg, R., 2003. The Party's Over: Oil, War and the Fate of Industrial Societies. New Society Publishers, Gabriola Island, British Columbia.
Heller, M., 1998. The tragedy of the anticommons: property in the transition from Marx to markets. Harvard Law Review 111, 621–688.
Huberman, D., Leipprand, T., 2006. Developing International Payments for Ecosystem Services: A Technical Discussion. UNEP, Geneva.
IMF, 2009. World Economic Outlook Database, 2009. International Monetary Fund, Washington, DC.
IPCC, 2007a. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the IPCC. Cambridge University Press, Cambridge.
IPCC, 2007b. Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.
IPCC, 2007c. Climate Change 2007: Synthesis Report. Summary for Policymakers. Cambridge University Press, Cambridge.
IPCC, 2007d. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.
Jackson, T., 2009. Prosperity without Growth? — The Transition to a Sustainable Economy. Earthscan, Sterling, VA.
James, A., Gaston, K.J., Balmford, A., 2001. Can we afford to conserve biodiversity? BioScience 51, 43–52.
Kahn, J.R., Franceschi, D., 2006. Beyond Kyoto: a tax-based system for the global reduction of greenhouse gas emissions. Ecological Economics 58, 778–787.
Kaul, I., Goulven, K.L., Schnupf, M. (Eds.), 2002. Financing Global Public Goods: New Tools for New Challenges: A Policy Dialogue. United Nations Development Program, New York.
Kerr, J.T., and M. Ostrovsky. 2003. From space to species: ecological applications for remote sensing. Trends in Ecology and Evolution 18:299–305.
Kumar, S., Managi, S., 2009. Compensation for environmental services and intergovernmental fiscal transfers: the case of India. Ecological Economics 68, 3052–3059.
Landell-Mills, N., Porras, I.T., 2002. Silver Bullet or Fools' Gold? A Global Review of Markets for Forest Environmental Services and their Impact on the Poor. International Institute for Environment and Development, London.
Limburg, K.E., O'Neill, R.V., Costanza, R., Farber, S., 2002. Complex systems and valuation. Ecological Economics 41, 409–420.
Lohman, L., editor. 2006. Carbon Trading: A critical conversation on climate change, privatisation and power. Dag Hammarskjold Foundation, Durban Group for Climate Justice and the Corner House, Uppsala, Sweden.
Loureiro, W. 2002. Contribuição do ICMS Ecológico a Conservação da Biodiversidade no Estado do Paraná. Tese de Doutorado. Engenharia Florestal. Universidade Federal do Parana, Curitiba.
Martinez-Alier, J., Munda, G., O'Neill, J., 1998. Weak comparability of values as a foundation for ecological economics. Ecological Economics 26, 277–286.

May, P., Neto, F.V., Denardin, V., Loureiro, W. (Eds.), 2002. Using Fiscal Instruments to Encourage Conservation: Municpal Responses to the Ecologica Value Added Tax in Parana and Minas Gerais, Brazil. Earthscan Publications, Sterling, Virginia.
Meinshausen, M., 2006. What does a 2 °C target mean for greenhouse gas concentrations? A brief analysis based on multi-gas emission pathways and several climate sensitivity uncertainty estimates. In: Schellnhuber, H.J., Cramer, W., Nakicenovic, N., Wigley, T., Yohe, G. (Eds.), Avoiding Dangerous Climate Change. Cambridge University Press, Cambridge, pp. 265–280.
Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Synthesis. Island Press, Washington, DC.
Mukerjee, M., 2009. A Mechanism of Hot Air. Scientific American 300, 18–21.
Naeem, S., 1998. Species redundancy and ecosystem reliability. Conservation Biology 12, 39–45.
Nepstad, D., Tohver, I.M., Ray, D., Moutinho, P., Cardinot, G., 2007. Mortality of large trees and Lianas following experimental drought in an Amazon Forest. Ecology 88, 2259–2269.
Nordhaus, W., 2007. Critical assumptions in the Stern Review on climate change. Science 317, 201–202.
Nordhaus, W., 2008. A Question of Balance: Weighing the Options on Global Warming Policies. Yale University Press, New Haven.
Odum, E.P., 1989. Ecology and our Endangered Life-Support Systems. Sinauer Associates Inc., Sunderland, MA.
Olson Jr., M., 1969. The principle of “Fiscal Equivalence”: the division of responsibilities among different levels of government. The American Economic Review 59, 479–487.
Pagiola, S., Bishop, J., Landell-Mills, N. (Eds.), 2002. Selling Forest Environmental Services: Market Based Mechanisms for Conservation and Development. Earthscan, Sterling, Virginia.
Pagiola, S., Agostini, P., Gobbi, J., Haan, C.d., Ibrahim, M., 2004. Paying for Biodiversity Conservation Services in Agricultural Landscapes. Environment Department Paper No. 96. World Bank, Washington, DC.
Pearce, D., 2007. Do we really care about biodiversity? Environmental and Resource Economics 37, 313–333.
Pimm, S.L., Russell, G.J., G.J.L., Brooks, T.M., 1995. The future of biodiversity. Science 347–350.
Portney, P.R., Weyant, J.P. (Eds.), 1999. Discounting and Intergenerational Equity. Resources for the Future, Washington, D.C.
Rijnhout, L., Schauer, T. (Eds.), 2009. Socially Sustainable Economic Degrowth: Proceedings of a workshop in the European Parliament on April 16, 2009 upon invitation by Bart Staes MEP and The Greens / European Free Alliance. online: http://www.clubofrome.at/2009/degrowth/proceedings.html.
Ring, I., 2008. Integrating local ecological services into intergovernmental fiscal transfers: the case of the ecological ICMS in Brazil. Land Use Policy 25, 485–497.
Rockstrom, J., Steffen, W., Noone, K., Persson, A., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sorlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A., 2009. A safe operating space for humanity. Nature 461, 472–475.
Salati, E., 1987. The forest and the hydrological cycle. In: Dickinson, R. (Ed.), The Geophysiology of Amazonia: Vegetation and Climate Interactions. John Wiley and Sons, New York, pp. 273–296.
Salati, E., Vose, P.B., 1984. Amazon Basin: a system in equilibrium. Science 225, 129–138.
Salzman, J., 2005. Creating markets for ecosystem services: notes from the field. New York University Law Review 80, 870–961.
Sandler, T., 1993. Tropical deforestation: markets and market failures. Land Economics 3, 225–233.
Sandler, T., 1998. Global and regional public goods: a prognosis for collective action. Fiscal Studies 19, 221–247.
Schelling, T.C., 2007. Greenhouse effect. In: Henderson, D.R. (Ed.), The Concise Encyclopedia of Economics. Liberty Fund, Inc.
Scotchmer, S., 1991. Standing on the shoulders of giants: cumulative research and the patent law. Journal of Economic Perspectives 5, 29–41.
Stern, N., 2006. Stern Review: The Economics of Climate Change. Cambridge University Press, Cambridge.
Stiglitz, J., 1999. Knowledge as a global public good. In: Kaul, I., Grunberg, I., Stern, M.A. (Eds.), Global Public Goods: International Cooperation in the 21st Century. Oxford University Press, New York.
TEEB, 2008. The Economics of Ecosystems and BIodiversity. European Communities, Brussels.
Tilman, D., Downing, J.A., 1994. Biodiversity and stability in grasslands. Nature 367, 363–365.
Tollefson, J., 2009. Cutting out the chemicals. Nature 457, 518–519.
Turner, W.R., Brandon, K., Brooks, T.M., Costanza, R., d. Fonseca, G.A.B., Portela, R., 2007. Global conservation of biodiversity and ecosystem services. BioScience 24, 868–873.
UNDP-GEF, 1998. GEF Operational Strategy. United Nations Development Program, New York.
UNFCCC. 1998. The Kyoto Protocol to the convention on climate change. Climate change secretariat/UNEP, New York.
Vatn, A., Bromley, D.W., 1994. Choices without prices without apologies. Journal of Environmental Economics and Management 26, 129–148.
Venter, O., Laurance, W.F., Iwamura, T., Wilson, K.A., Fuller, R.A., Possingham, H.P., 2009. Harnessing carbon payments to protect biodiversity. Science 326, 1368.
Victor, D. 2004. Climate Change: Debating America's Policy Options. Council on Foreign Relations Policy Initiatives. Council on Foreign Relations, New York, New York.
Victor, P., 2008. Managing Without Growth: Slower by Design, not Disaster. Edward Elgar Publishing, Cheltenham.
Vogel, J.H., 1997. The successful use of econmic instruments to foster sustainable use of biodiversity: six case studies from Latin America and the Caribbean. Biopolicy 2, 1–44.
Voinov, A., Farley, J., 2007. Reconciling sustainability, systems theory and discounting. Ecological Economics 63, 104–113.
Wara, M., 2007. Is the global carbon market working? Nature 445, 595–596.
Weitzman, M.L., 1998. Why the far-distant future should be discounted at its lowest possible rate. Journal of Environmental Economics and Management 36, 201–208.
Welch, D., 2007. Quoted in N. Davies (2007) The inconvenient truth about the carbon offset industry. The Guardian, Saturday 16 June 2007.
Wilson, E.O., 2002. The Future of Life. Alfred A. Knopf, New York.
World Trade Organization, 2006. WTO Statistics Database. World Trade Organization.
Worm, B., Barbier, E.B., Beaumont, N., Duffy, J.E., Folke, C., Halpern, B.S., Jackson, J.B.C., Lotze, H.K., Micheli, F., Palumbi, S.R., Sala, E., Selkoe, K.A., Stachowicz, J.J., Watson, R., 2006. Impacts of biodiversity loss on ocean ecosystem services. Science 314, 787–790.
Wunder, S., 2007. The efficiency of payments for environmental services in tropical conservation. Conservation Biology 21, 48–58.