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The economics of restoration: looking back and leaping forward

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Since the publication of the Millennium Ecosystem Assessment in 2005 there has been a surge of interest in ecological restoration (ER) to recover biodiversity, re-establish ecosystem functioning and connectivity, and reactivate the delivery of ecosystem services. In policy spheres, there have also been repeated calls for expansion of restoration efforts. In many countries, new legislation now requires some form of restoration and/or a form of offset investment. All of this will require major increases in financial allocations toward restoration science, technology, and implementation, and much more detailed valuation techniques. The *economics of restoration* is a new field emerging to support these needs. Our paper here starts with an analysis of the articles and reviews published on this broad subject from 1928 to 2012, as captured in the Scopus academic search platform. Our goal is to present and summarize what has been said and done in this area to date. Next, we map out one possible way forward, illustrated by examples and based on a coherent bundle of decision parameters related to the economics of ER and, more broadly, to the restoration of natural capital. The restoration of natural capital is defined as activities that integrate investment in, and replenishment of, natural capital stocks to improve the flows of ecosystem goods and services, and the preservation of biodiversity, while enhancing all aspects of human well-being. We give special attention to system dynamic approaches and other promising tools and techniques.

Keywords: economics of restoration; restoration of natural capital; ecosystem services; benefit–cost analysis; system dynamics; discounting

Introduction

> *Here is the means to end the great extinction spasm. The next century will, I believe, be the era of restoration in ecology.*
>
> —E.O. Wilson[1]

> *The restoration of natural capital is arguably one of the most radical ideas to emerge in recent years as it links two imperatives whose exponents have been at loggerheads for decades. These are the need to protect biodiversity and conserve natural resources as espoused by conservationists and environmentalists, and the demand for natural resources as dictated by economists and society at large, at local, regional, national and international scales.*
>
> —Aronson *et al.*[2]

The justification for the bold statements cited above has three parts. First, there is growing recognition that hands-on ecological restoration (ER) and rehabilitation are required as part of the suite of responses society must make to address and reverse widespread ecosystem degradation, desertification, anthropogenic climate change, and the unprecedented loss of biodiversity for which humans are responsible. Second, there is growing recognition that it is the dwindling stocks of natural capital that represent the limiting factor to economic growth, and not human-made capital, as it used to be[4]

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(H. Daly, personal communication). Third, economists and ecologists now increasingly agree that there is an urgent need to actively augment the dwindling natural capital stocks upon which all economies depend. This will require more than technology and ecological understanding, and indeed a true paradigm shift regarding technology, nature management, human economic and social behavior, and financial investments in the restoration of natural capital is needed.[3] What we would call *restoring natural capital thinking*, or a *culture of restoration*, starts with the recognition that through effective ER and related activities, it is possible to slow and even reverse the loss of at least some forms of natural capital and thereby enhance the quality, quantity, and flows of ecosystem services to people while also slowing the alarming erosion of biodiversity that current human activities have unleashed. This approach is far more ambitious than those who promote no net loss; we think much more than that is possible, and, indeed, desirable, given the many decades of environmental consumption that have taken place without concurrent investment in replenishment.

Regarding the term *economics of restoration*, Paul Hawken[4] deserves credit for his ground-breaking books, *The Ecology of Commerce*[5] and *Natural Capitalism*,[6] wherein the term *restorative economics* and its opposite *destructive economics* were coined. Although progress has been made conceptually,[7–9] too few practical applications have been achieved during the last 15 years, especially in the crucial areas of valuation and financing.[10,11] Concurrently, there has been far too little work on how to actually measure and monitor the economic effects of restoration.[12] Partly for this reason, it is still very uncommon for those actually planning and conducting restoration to consider the economic or socioeconomic benefits and impacts of restoration.[13] It seems clear that if restoration scientists and practitioners were to work closely with economists to systematically plan for the evaluation and monitoring of economic values and impacts derived from restoration, this unsatisfactory situation could quickly change. In other words, it would become "increasingly easier to detect the economic effects of future restoration projects, choose economically efficient ones to implement, and demonstrate their economic outcomes."[12,14] We argue that, especially since the publication of the Millennium Ecosystem Assessment (MA),[15] an appropriate framework already exists to consider restoration not as a cost item on a project and/or government budget to undo wrongs of the past, but rather as a value-generating option. The MA clearly demonstrated the link between ecosystem goods and services (EGS) and human welfare.[15] It showed that once an economy begins to lose EGS, it is forfeiting future development options. Conversely, if it invests in recovering these services through the restoration of natural capital, such efforts could contribute meaningfully to economic development, provided they are planned and carried out appropriately.

Bridging natural and economic sciences to inform and refine restoration

One problem has clearly been that economists and most of those people engaged in ER (and biodiversity conservation and conservation science) generally do not use the same language.[16] The idea of actively restoring or replenishing stocks of natural capital can serve as a bridge between environmental and natural sciences, on the one hand, and economics on the other. Clearly, a component of the emerging transdisciplinary field of sustainability science should be to assess and advise where and how to allocate scare financial resources to this enterprise.[2,17–21] Another motivating factor is the strong theoretical advances made with respect to payments for ecosystem goods and services (PES) which require both an assessment of the value of the locally or regionally available EGS, be it through the careful management and stewardship thereof, and/or restoration, and the costs of doing so.[22] However, large obstacles still exist to a practical and economic application of PES including the establishment of property rights, execution of contracts, methods for monitoring performance, and the creation of markets.[23]

There is an obvious link between such projects to Reducing Emissions from Deforestation and Forest Degradation (REDD+/++) (such as http://www.planvivo.org/) and associated projects with respect to carbon sequestration in the quest for climate change mitigation and adaptation, with carbon and related projects being a subset of the larger group of projects linking economics and environmental *cum* natural sciences.[24–26] Building on the MA,[15] the United Nations' TEEB project[27]—the Economics of Ecosystems and Biodiversity project—provided a strong stimulus for the new focus on the importance for economists, politicians, entrepreneurs, and other decision makers to pay more attention to restoration.[12] We propose there is an emerging and legitimate field of enquiry, experimentation, and application to policy in public and private sectors, as well as international negotiations related to the environment, that could be called the economics of restoration.

As a bridge between economics and environmental *cum* natural sciences, the economics of restoration will help to advance the kind of use-inspired research urgently called for today.[28] In simpler language, it can help economists and ecologists, along with other scientists and professionals, to work together to address the fundamental problems facing communities and indeed humanity today. The intellectual enquiry at stake is quintessentially interdisciplinary, or better still, transdisciplinary. Yet, it also represents a return to the earliest foundations of economic science (see Ref. 29). Here we reflect on the development of the economics of restoration over the past century, with special focus on the last 15 years. Our goal is to help advance the collective thinking and discourse about the future of the economics of restoration and how to address the challenges we must face and the opportunities we must embrace. We start with an analysis of the articles and reviews published to date on this subject (1928–2012) as captured in Scopus. We build on this analysis to help formulate a new action plan that incorporates collaborative ecological and economic research and application related to the valuing and financing of ecosystem restoration. Our goal is to improve institutional and legal frameworks for ER options that will also inform better ecosystem management models, improve the science and technology of restoration, and help control and regulate destructive economic activities.

Economics of restoration: looking back

As the economics of restoration is not yet established as a formal field of enquiry recognized by tertiary institutions or scientific journals, a web-based search on that precise term was unlikely to yield meaningful results. Consequently, a much broader search focus was adopted. Using the Scopus, Google Scholar, and Science Direct academic platforms, we searched for the following terms: "restore" or "restoration;" and "economy" or "economics;" and "ecology" or "environment" or "ecosystem."

The Science Direct enquiry yielded less than 100 hits, all of which were also captured by Scopus, which yielded 675 results for the period 1928–2012. The results from Google Scholar, however, yielded a much larger collection and broader spectrum of documents, including books, presentations, and proceedings. However, the manner in which the results from Google Scholar are returned does not allow eliminating documents in the gray literature and avoiding double counting. It therefore renders a diagnostic assessment of the results quite difficult. Consequently, we decided to only use the articles and reviews from Scopus. The search was conducted on December 28, 2012 and repeated on March 7, 2013 for verification. The second search yielded 11 additional papers for 2012; hence, these latter results were used in the analysis that follows.

While the list of papers (from the Scopus search) dates back to 1928 (Thorndike[30]), it only provides a detailed citation analysis for papers since 1996. The 25 papers in the list of 675 publications published before 1996 were therefore excluded from the analysis, reducing the sample to 650 papers. This pruning also removed all the papers that met the search criteria, but were clearly irrelevant to the topic of discussion (e.g., if they focused on restorative dentistry).

The results of the review, considering the number of papers per year, numbers of citations, and the *h*-index, are presented in Figure 1. (The *h*-index refers to the number of times a number of papers have been cited, e.g., an *h*-index of 13 means that 13 papers have been cited at least 13 times or more; the higher the score, the better.) From only 10 relevant papers in 1996, the number of papers per year rose to 90 in 2011 and 68 in 2012. No specific reason could be found to explain the decline observed from 2011 to 2012. Only time will tell if this 1-year dip is of significance. A notably rapid increase in papers took place between 2007 and 2011. This was very likely linked to the publication of the above-cited MA report[15] and also the first major TEEB report[27] in 2010. It is, however, the number of citations that deserves special attention. Citations increased from three (in 1996) to 1549 (in 2012), with an aggregate number of citations of 6970 and an *h*-index of 37 over this period. Although it is to be expected that the number of citations had to be low initially (since Scopus began detailed analysis of tracking paper citations only in 1996), the >500-fold increase over a

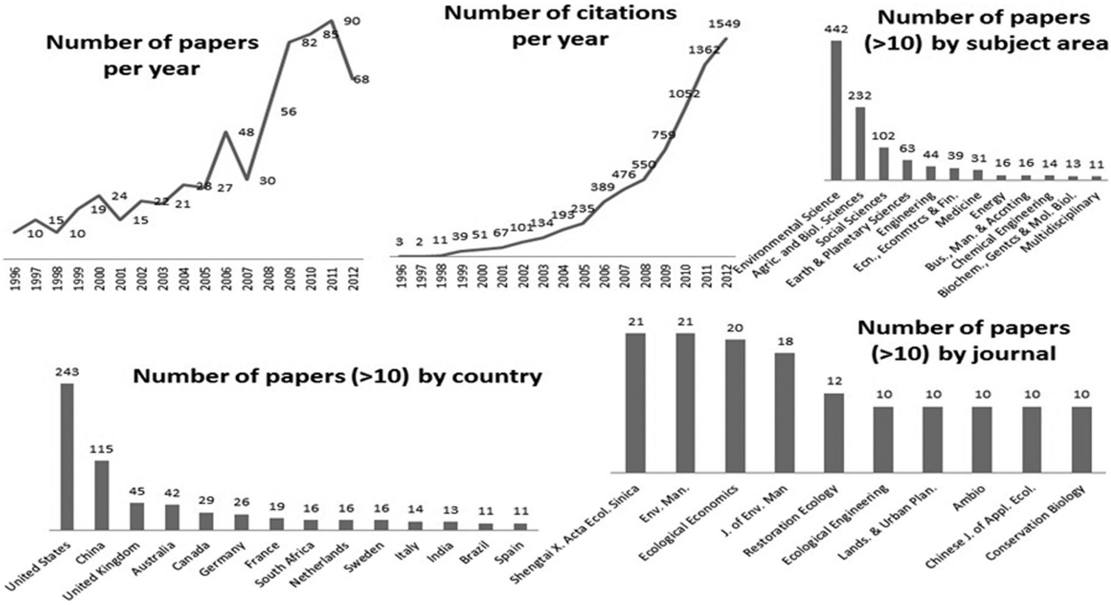

Figure 1. Analysis of 650 articles and reviews listed in Scopus (1996–2012) based on a search carried out on March 7, 2013 (for "restoration" or "restore;" and "economy" or "economics;" and "ecology" or "environment" or "ecosystem") in titles, abstracts, and/or keywords.

16-year period is a strong indication of the increasing interest in papers that cover this topic. Table 1 provides a list of the top 26 papers; that is, the papers with more than 50 citations each.

Papers in environmental sciences (442) dominate, followed by those in agriculture and biological sciences (232) and social sciences (102). This result is not surprising, given the specific focus area and the relatively small number of papers that are classified as pertaining to economics, econometrics, and finance (39). Further, given the infancy of the subject and the historical link of restoration ecology and conservation biology, this trend could have been expected. However, a strong social sciences assessment is also required, as we will discuss later. (Note that a paper can have multiple subject allocations, which in turn gives rise to a total greater than 650.)

Papers from, and focusing on, the United States (243) and China (115) dominate the literature. It is, however, important to note the strong representation of three BRICS (Brazil, Russia, India, China, and South Africa) countries, namely South Africa (16), India (13), and Brazil (11). Each of these countries contributed more than five papers, and all three stand out in a list largely dominated by richer, more industrially developed countries. The spread of journals covering this topic also reflects the international spread, with Chinese and American-based journals topping the most-preferred journal list, led by journals such as *Shengtai X. Acta Ecologica Sinica* (21), *Environmental Management* (21), *Ecological Economics* (20), and the *Journal of Environmental Management* (18). It is noteworthy that only *Ecological Economics* had both a relatively high number of papers and a high number of citations, while the other three top journals—judging by the number of relevant papers—were not highly cited. Possibly, this merely signals a fractured and underdeveloped state of research in this quintessentially interdisciplinary field.

Economics of restoration: leaping forward

ER can be defined "as the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed."[31] One could add that ER is a process that recovers and improves the functionality of ecosystems within landscapes and is supported by the scientific discipline of restoration ecology.[2] ER assists ecosystem recovery, augments biodiversity, and generates ecosystem services for use (and enjoyment) by both humans and nature. Humans

Table 1. **The top 26 papers in the survey: papers with more than 50 citations**

Authors	Journal	Year	Title	Citations
E.S. Bernhardt *et al.*	*Science*	2005	Synthesizing U.S. river restoration efforts	417
C.D. Allen, J.T. Klingel, M. Savage, *et al.*	*Ecological Applications*	2002	Ecological restoration of Southwestern ponderosa pine ecosystems: a broad perspective	314
P. Smith, D. Martino, Z. Cai, *et al.*	*Philosophical Transactions of the Royal Society B: Biological Sciences*	2008	Greenhouse gas mitigation in agriculture	213
J.R. Karr	*Freshwater Biology*	1999	Defining and measuring river health	191
M.R. Brown and S. Ulgiati	*Ecological Engineering*	1997	Energy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation	189
T. Mitche, J.K. Zimmerman, J.B. Pascarella, *et al.*	*Restoration Ecology*	2000	Forest regeneration in a chronosequence of tropical abandoned pastures: implications for restoration ecology	177
J. Loomis, P. Kent, L. Strange, *et al.*	*Ecological Economics*	2000	Measuring the total economic value of restoring ecosystem services in an impaired river basin: results from a contingent valuation survey	176
J.A. Patz, P. Daszak, G.M. Tabor, *et al.*	*Environmental Health Perspectives*	2004	Unhealthy landscapes: policy recommendations on land use change and infectious disease emergence	154
R. Lal	*Critical Reviews in Plant Sciences*	1998	Soil erosion impact on agronomic productivity and environment quality	133
A.H. Arthington and B.J. Pusey	*River Research and Applications*	2003	Flow restoration and protection in Australian rivers	119
W.L. Graf	*Annals of the Association of American Geographers*	2001	Damage control: restoring the physical integrity of America's rivers	118
S. Opricovic and G.-H Tzeng	*Computer-Aided Civil and Infrastructure Engineering*	2002	Multicriteria planning of postearthquake sustainable reconstruction	91
D.E. Canfield, A.N. Glazer, and P.G. Falkowski	*Science*	2010	The evolution and future of earth's nitrogen cycle	87
B.D. Richter and G.A. Thomas	*Ecology and Society*	2007	Restoring environmental flows by modifying dam operations	76
J.K. Turpie, C. Marais, and J.N. Blignaut	*Ecological Economics*	2008	The working for water programme: evolution of a payment for ecosystem services mechanism that addresses both poverty and ecosystem service delivery in South Africa	75
R. Biggs, S.R. Carpenter, and W.A. Brock	*Proceedings of the National Academy of Sciences of the United States of America*	2009	Turning back from the brink: detecting an impending regime shift in time to avert it	73

Continued

Table 1. *Continued*

Authors	Journal	Year	Title	Citations
M.S. Li	*Science of the Total Environment*	2006	Ecological restoration of mine land with particular reference to the metalliferous mine wasteland in China: a review of research and practice	70
A. Bradshaw	*Landscape and Urban Planning*	2000	The use of natural processes in reclamation—advantages and difficulties	67
R. Weber, C. Gaus, M. Tysklind, *et al.*	*Environmental Science and Pollution Research*	2008	Dioxin- and POP-contaminated sites—contemporary and future relevance and challenges: Overview on background, aims, and scope of the series	66
R.S. Pulwarty and K.T. Redmond	*Bulletin of the American Meteorological Society*	1997	Climate and Salmon restoration in the Columbia River Basin: the role and usability of seasonal forecasts	66
G. Wade Miller	*Desalination*	2006	Integrated concepts in water reuse: managing global water needs	64
L. Pejchar and H.A. Mooney	*Trends in Ecology and Evolution*	2009	Invasive species, ecosystem services, and human well-being	61
M.V. Santelmann *et al.*	*Landscape Ecology*	2004	Assessing alternative futures for agriculture in Iowa, U.S.A.	60
C.J. Donlan, J. Berger, C.E. Bock, *et al.*	*American Naturalist*	2006	Pleistocene rewilding: an optimistic agenda for 21st century conservation	56
C.M. Stickler, D.C. Nepstad, M.T. Coe, *et al.*	*Global Change Biology*	2009	The potential ecological costs and co-benefits of REDD: a critical review and case study from the Amazon region	53
M.A. Palmer and S. Filoso	*Science*	2009	Restoration of ecosystem services for environmental markets	53

are an integral part of ecosystems and, therefore, have the responsibility to manage and restore degraded systems. Hence, the concept of restoring natural capital (RNC) is broader than that of ecological restoration, namely "any activity that integrates investment in, and replenishment of, natural capital stocks to improve the flows of ecosystem goods and services, while enhancing all aspects of human well-being."[7] Thus, ecological amelioration and ecological and economic revamping of production systems, resource extraction systems, and transport systems can also contribute to RNC. Furthermore, environmental and ecological education, outreach, and capacity building also contribute. The economists most likely to take an interest in such activities are those trained in environmental or ecological economics.

Environmental economics is often thought of as the environmental branch of neoclassical economics, that is, the branch of economics that imagines a world in which there is perfect information, perfect resource substitution, and no scarcity.[32] In contrast, ecological economics is largely based on the classical school of economic thought in which land is the key production factor, and when it is in short supply, it represents the major constraining role to economic growth. In addition, this new approach is also influenced by systems ecology and therefore embraces the realities of ecological scale, the nested hierarchy of ecosystems, and the finite carrying capacity of the earth. All of these biological and ecological constraints limit human choices and provide very distinct limits to resource-intensive economic growth. These perspectives are based on ecological economics' view on the prevalence of absolute scarcity, which is bounded by the laws of thermodynamics.[33] This implies that perfect resource substitution is not possible, that is, human-made capital can only in part replace and/or substitute for natural capital. Ecological economics is, therefore, also a study of the interrelationships between economy and ecosystems in the light of biophysical limits, with a specific focus on stewardship; hence, peoples' norms and value systems are important and the outcome of economic and natural resource management decision are value laden.[34,35] This is in stark contrast to environmental economics, which considers humans to be value-free utility-maximizing agents that base their decisions purely on rational analysis and calculus.[36]

Often the purpose of the restoration of degraded ecosystems is to undo or offset the impacts of human-induced damage and degradation. One of the objectives from an economics perspective is to improve the flow of ecosystem goods and services (provisioning, regulating, supporting, and cultural) to people. In addition to the disciplines of ecology, biology, and genetics, the science, business, and practice of restoration should also draw on the social sciences, including economics. These disciplines must be used to complement the study of ecological, geological, and hydrological processes and principles, as well as to inform which interventions and which scales are the most timely and important for all relevant stakeholders. In other words, as noted by Van Dover *et al.*,[37] decision-making parameters for restoration projects, especially large-scale ones, should not only include ecological, geomorphological, and hydrological attributes but also socioeconomic and technological ones. Applying the principles of ecological economics, for example, will assist in the prioritization of restoration objectives and targets, potentially improve the effectiveness of interventions undertaken, and help in the application of restoration of natural capital thinking when confronted with scarcity of resources. Environmental economics tools will do likewise, yet its treatment of scarcity and resource substitution is completely different, leading to a potentially different set of recommendations. For example, if a specific natural resource is very scarce, but cheaper than its manufactured counterpart or substitute, the price signal would suggest the use of the natural resource despite its scarcity.

Here we do not wish to embark on a full and detailed analysis and exposition of the tools available to environmental and ecological economists, but rather focus the discussion on a much more strategic, or higher, level. We address the issue of risk and resource allocation. These are issues relevant to all the relevant schools of thought and the new culture of restoration we see as potentially emerging. Although economics cannot provide the motivation for restoration per se, the economics of restoration can, and should, play a meaningful role in answering these strategic questions, such as (1) under which conditions markets could contribute to restoration, and (2) the identification of the risk–reward profile of proposed and/or historic restoration activities. In short, there is an overlap whereby economic tools could assist in decision making with respect to restoration in a world constrained by finite resources, assist in prioritization, and seek to develop indicators with respect to efficiency, continually seeking methods for improvement. These tools could assist those engaged in ER with the planning, execution, and evaluation phases as well as in interactions with a local community, or a broader society, so as communicate the contribution of restoration and help facilitate the process of negotiation and compromise among stakeholders. They can also help determine where restoration, in the sense of the Society for Ecological Restoration (SER),[31] is not the best option within a broader RNC program. Indeed, in some landscape units, functional rehabilitation of agro-ecosystems and other production or utilitarian systems, or reallocation of deeply transformed or degraded lands may be the better option.

The economics of restoration can, therefore, be depicted as an area of overlap between two interlocking disciplines, namely restoration ecology, on the one hand, and ecological and environmental economics, on the other (Fig. 2). This requires a shared vision among economists and ecologists[7] who agree to work together toward developing a combined toolbox and analytical toolkit.

Some tools that could be used in this analysis include the economic valuation of natural resources as well as economic evaluation techniques such as a cost–benefit analysis, supported by integrated ecological–economics system dynamics (SD) modeling approaches.

Cost and benefits of restoration

In a recent survey compiling both the benefits and the costs of restoration,[38] it was pointed out that the methods to determine the benefits of restoration have been steadily better developed and

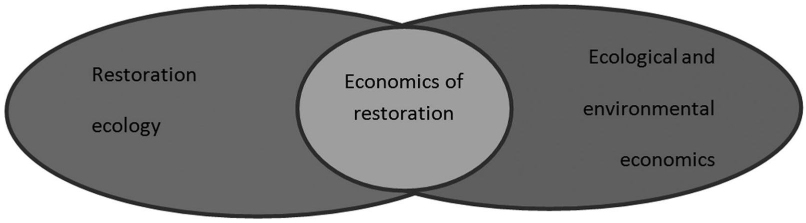

Figure 2. Economics of restoration: an integrator between restoration ecology and economics.

reported on in peer-reviewed journals over the past two decades. The benefits are often reported in association with restoration studies. However, these reports seldom differentiate whether the benefits perceived were marketable, and if so to whom by whom, or whether they were economy-wide benefits to society. Not considering the distributional impacts and/or the difference between marketable and economy-wide benefits to society can, and often does, lead to confusion. This is due to the fact that benefits arising from restoration are often public benefits, while the costs incurred are often private.

In the same survey,[38] it was noted that the way in which the cost of restoration is determined varies greatly. In some instances total cost is determined, while in others it is average cost. Sometimes it only includes private financial cost, and no in-kind contribution is indicated. Often total cost is mentioned, but not in comparison to a unit such as an area or distance, for example, kilometers of river front restored. These differences not only make comparisons very difficult, but also impede the development of economics of restoration going forward, as it is difficult to build a track record of reference cases that could be used as benchmarks.

In other surveys, it has also been found that there is generally poor communication between the people conducting research on restoration, or practicing ecosystem restoration, on the one hand, and the beneficiaries thereof, on the other.[13,39,40] Research and practice of the economics of restoration are, therefore, rarely requested or driven by those who are likely to benefit most from the outcome. In developing countries, in particular, this is a recipe for failure, and conceptual advances in many of the publications cited above render this disconnect anachronistic.

Although we would like to think that ER is akin to pressing an undo button, it is not.[41] Not only is it rarely possible to erase the historic scar, it is also not possible to do something even remotely approximating that in less than decades or centuries.[42] Time therefore does matter, and there is much room for improvement in restoration science and technology. Unfortunately, most applications of benefit–cost models accept linearity with respect to time. Although an active, time-based intervention could, for the purposes of economic analysis, be compared to an engineering exercise, the actual application of restoration occurs within the context of dynamic, complex ecosystems—an active system that must respond to often large and unpredictable changes at various scales in space and time. Thus, ecosystems undergoing restoration activities are subject to myriad interrelationships and feedback associated with events such as fires, droughts, floods, and other events resulting in change that occurs at spatial scales well beyond the specific ecosystem or landscape targeted.

It is imperative for ecologists and economists to collaborate and to specify a minimal (lower bound) objective for the restoration of ecosystem state variables (or desired outcomes). Given the scarcity of restoration funding, the need arises to determine the least-cost strategy. In conjunction with each other, they would therefore like to find the restoration strategy that achieves that objective at least cost based on a range of restoration options or pathways. Several tools, such as simulation, dynamic programming, or SD modeling can be used to achieve this objective. We elaborate on the use of SD modeling as a prime example of such.

SD modeling

One way to address complex interactions and dynamics over time, in the context of conducting economics on restoration, is SD modeling.[9] In the application of Crookes *et al.*,[9] benefit–cost analysis is still the main analytical method used, allowing for complexity and time variance in the interrelationships between socioeconomic and ecological systems. Such an approach requires a much deeper understanding of ecosystem behavior than is used in most conventional benefit–costs analyses. As mentioned above, ecologists and economists need to communicate better on how they perceive the aspects of reality that they are studying, and together build a toolbox, a vision, and a tradition of undertaking integrated ecological–economic studies, among other things, with the help of SD modeling. SD modeling involves the construction of a number of stock–flow relationships among a potentially very large number of parameters. As an example here, the biomass of a standing forest can be considered a stock, delivering a suite of services such as carbon sequestration and soil stabilization. These services are flows that depend on the rate of carbon absorption and the rate at which soil movement is contained. Flows are, per definition, time- and space-dependent (i.e., a rate per area over some definition of time, often a year). Stocks, however, accumulate and contract over time and space depending on the size of the opening stock and the change in the growth or death of such stock[43–45]

SD modeling is a technical tool but also an aid within a process of social learning for people from different backgrounds. It can provide input to, assist in the formulation of, and make use of a range of different metrics applicable to restoration. Metrics that are very subject specific can now be integrated with other metrics from other disciplines into a system of equations leading to a more comprehensive view reflecting an improved view of the state of the environment, the drivers of change, and the perceived impacts of either doing nothing or undertaking ecosystem restoration.

The complexity of the biophysical world over time is a pertinent input into benefit–cost analysis, yielding an endogenous stream of costs and benefits over time. With conventional benefit–cost analysis comes the issue of the use of a discount rate. However, discounting the future becomes less of an issue when SD modeling approaches are used. The power of the discount rate is such that it drives the determination of the net present value to a very large extent. The outcome and/or answers are therefore linked to an exogenously determined and arbitrarily chosen variable that averages out many different people's time perception of money. One way to neutralize the effect of the discount rate is to consider a range of options and/or scenarios and to keep the discount rate constant. The variation in the outcome is likely to be driven by changes endogenous to the restoration event, such as any possible changes in the stream of costs and/or benefits over time. The future is simulated, rather than discounted, opening up various options for the decision maker under which restoration may be viable. In restoration projects with a high degree of complexity and uncertainty, care should be taken not to evaluate them based on outcomes in which the discount rate played a predominant role in the decision outcome. It should be noted that, given the risk associated with the complexity and uncertainty in biophysical and socioecological systems, it is possible to consider, within the context of SD modeling, Monte Carlo–type simulations. This, in addition to "what if" scenarios, can be used to determine various tipping points and thresholds in the system.

Having discussed some of the tools, we now review two case studies where attempts are made to apply these tools related to cost effectiveness and also the use of restoration in offset programs.

Case 1: Studies of cost-effectiveness and examples from Brazil and the deep sea

Economic analyses of restoration are now being used across a wide range of spatial scales; governance policy and legislative contexts emerge as critical variables to be addressed. Notably, in São Paulo state, Brazil, legislation on forest ecosystem restoration has existed for almost 30 years, and is now under careful scrutiny and revision, thanks to cooperation among legislators, scientists, and various stakeholders.[46,47] Furthermore, almost no economics of restoration studies have been conducted. Brancalion *et al.*[48] compared cost effectiveness of five concurrent strategies for obtaining viable seeds of more than 100 species of native trees used by BioFlora, a leading native tree nursery and restoration service provider in São Paulo state, producing around 3 million seedlings per year. These authors evaluated the annual income earned from sales of seed obtained by a professional seed harvester, amateur seed harvesters, and a seed production cooperative, over a 2-year period. Total expenditure, value (in U.S. dollars) per species collected and value per exclusive species, that is species obtained through one strategy only, were compared. The result indicated that a mixture of strategies was most cost effective for the nursery, and increased the diversity of seeds obtained, as well as the number of plant functional groups represented in the restoration projects, and also increased the genetic diversity of seedlings used. This is critical both to the nursery and the client, since current São Paulo law requires that forest restoration achieve very high diversity of native trees (minimum 80 species) and encourages the incorporation of high genetic diversity. It is also, in theory, beneficial to society to the extent that the legislation requiring high tree diversity in restoration projects is ecologically well founded.

However, the laws in São Paulo state, and in Brazil generally, do not provide mechanisms to insure that restoration on private lands be economically viable, let alone profitable, for landowners; instead it is imposed—or perceived by landowners as being imposed—as a punishment of sorts, even when the deforestation at issue was not carried out by the present landowner. Accordingly, the economics of forest restoration in São Paulo state, and indeed throughout the coastal region of Brazil, is eliciting much reflection and study of opportunity costs and potential sources of revenue (e.g., see Ref. 49). There is a clear understanding among restoration economists and scientists in Brazil that legal requirements for compliance will not be sufficient given that most of the restoration to be undertaken will be on private lands.[52] In other words, unless restoration can be made to be financially viable for landowners, scaling up and connecting restored lands together, as biodiversity conservation interest require, will never be achieved. Brancalion *et al.*[49] are developing tangible strategies and models for landowners to integrate sources of income in restored forests on their lands, but for now legislation is lacking. The ecological–economic models and pilot studies may—in this case—help show the way forward. But direct compensation and other incentives and disincentives will probably be needed, along with straight-up economic benefits.

Indeed, this is true in all areas where restoration is being explored today, even in the deep sea where, for the first time, marine scientists, restoration ecologists, legal and economics experts of the seas, and mining and energy industry representatives have met to discuss the way forward for restoration.[37] In this context, the lack of clear governance of ecosystems in the deep sea is a major hindrance. The International Seabed Authority controls exploration for resources in the seabed itself (see http://www.isa.org.jm/en/home) but currently has no authority to impose restoration or compensation for residual damages caused by trawling, drilling, or mining. This situation will require review as stepped-up industrialization of the deep sea appears to be just around the corner.[51]

Case 2: Restoration as part of offset schemes and systems

Arguably, the economics of restoration must be approached as part of a bigger picture today, one involving mining, energy, agriculture, and other sectors—all within a regional planning context that, ideally, incorporates the vision of RNC. The default position for many today, in fact, is what is known as *no net loss*, for example, in the permitting procedures under the U.S. Clean Water Act (1972) for impacts on wetlands. Similarly, the performance standards of the International Finance Corporation, and in particular PS6, require no net loss for investments that impact natural environments and habitats.[52] The international standard on biodiversity offsets published by the Business and Biodiversity Offsets Programme (BEBOP), is built around this same principle objective (http://bbop.forest-trends.org/). Offsetting requires that actions be taken that generate gains on the ground, in exchange for the losses attributed to the residual impacts of the projects, which could not be avoided or reduced. The precise definition of these losses and gains is central for offset mechanisms.[53] However, many problems remain to be solved, including what constitutes equivalency or adequate trade-offs.

In Alberta province, western Canada, Habib *et al.*[54] studied the need for flexibility in biodiversity offset schemes for the burgeoning oil shale industry in a region with large expanses of relatively intact (undeveloped) boreal forest with high conservation value. In other words, this is a region where equivalency offsets are inappropriate. By contrast, in the highly transformed landscapes of New Zealand, restoration is a different proposition altogether and the economics of restoration are also.[55] However, two things are shared between these two examples, namely the need for economists to recognize ecological uncertainty and the need for those engaged in ER and related ameliorative interventions or ecosystem management to approach restoration in an holistic fashion, as part of a larger vision and planning process.

Prospectives

As the case studies discussed earlier are extremely encouraging, it seems that this emerging application of economics to the restoration of natural capital constitutes a fertile interface between ecology and economics and can provide a strong underpinning for three other emerging interdisciplinary fields, namely those focused on ecosystem services, sustainability, and ethics.[56] These are themes also discussed in Blignaut *et al.*[57] with respect to the restoration of degraded grasslands of the Drakensberg mountain range in South Africa, leading to much improved flows of ecosystem goods and services, a more vibrant local economy, and much more equitable allocation of resources. This outcome was a result of the participation of local stakeholders and the local community in the restoration process, and led to all stakeholders benefitting from improved land productivity. In addition, those who were active in the restoration process benefited by being remunerated for services provided.

Conclusions

The economics of restoration is a subject rapidly gaining ground, as indicated by the increase in number of relevant or related publications. From only 10 relevant papers in 1996, the number per year rose to 68 in 2012 and 90 in 2011, with a notably rapid increase between 2007 and 2011. This was very likely linked to the publication of the MA report[15] and also the first major TEEB report[27] in 2010. Citations increased from three (in 1996) to 1549 (in 2012), with an aggregate number of citations of 6970 and an *h*-index of 37 over this period.

This increase in the interest in the economics of restoration is due to an increasing recognition that, in a world characterized by (1) widespread and ongoing ecosystem degradation despite various ethical objections and the obvious biophysical limits of the earth to sustain the current rate of exploitation, (2) growing natural resource scarcity, (3) increasing per capita consumption of resources, and (4) rapidly growing human population, small-, medium-, and large-scale ecosystem restoration is imperative (see Ref. 58, among many others). However, financial resources for new investments for restoration must be found and justified. Although economics cannot provide the sole motivation for restoration per se, the economics of restoration can, and should, play a meaningful role in answering issues such as (1) under which conditions free markets for goods and services can contribute to making restoration financially attractive, and (2) how to determine the specific risk/reward profile of each proposed, ongoing, and historic restoration project of specific intervention. The economics of restoration can therefore assist in prioritization with respect to decision making on how to best make use of resources (financial, human, and otherwise) to augment natural resource stock through restoration. More specifically, economic science could assist in the prioritization of various biodiversity conservation and restoration requirements and responsibilities, both from ethical and legal perspectives. Such prioritization can help politicians, corporate heads, community leaders, and other policy and decision makers to make informed decisions at a time when the demand for ER is required to grow exponentially. It could also help in defining a culture of restoration that would allocate appropriate sums to the advancement and mainstreaming of ecosystem restoration in all biomes of the Earth.

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Conflicts of interest

The authors declare no conflicts of interest.

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