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Shaping global environmental decisions using socio-ecological models

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One of the most ambitious ecological studies of the past few decades was the Millennium Ecosystem Assessment (MA), which examined the consequences of ecosystem change for human well-being. The MA developed global ecological scenarios as a process to inform policy options, despite enormous uncertainties. These scenarios were based on an interlocking suite of models that forecast the future. Following the recent completion and publication of the MA, there is now movement towards making the value of ecosystem services an integral part of key policy decisions. Here, we review the MA approach and suggest areas where immediate progress can be made to increase the likelihood that decision-makers will embrace the vision of assessments such as the MA.

The lure of global ecological models

Perhaps the earliest global ecology model was Thomas Malthus' *Essay on the Principle of Population*, published in 1798 [1]. With pencil and paper, Malthus contrasted geometric population growth with arithmetic growth of agricultural production. He deduced an inescapably gloomy future for the world, with population growth continually outstripping food production. Some of Malthus's critics gloat that his doom-and-gloom prediction never came to pass, whereas others caution that he was just ahead of his time. More than 200 years after Malthus published his essay, *Science* published the article, 'Will Malthus continue to be wrong?' [2]. Demographers predict a leveling off of the global population at 10 billion by 2100 [2]. What this means for strife, hunger and environmental quality is still unclear, but the resolute gloom of Malthus does not seem to be as inevitable as Malthus thought. The most ambitious and comprehensive answer to Malthus can be found in the 2005 release of the Millennium Ecosystem Assessment (MA), which examines the future quality of life for humans on our planet [3].

The MA was conceived and launched by Walt Reid, after over a decade of experience in Washington DC working for the World Resources Institute (http://www.wri.org/). In Reid's view, the MA needed to mimic the IPCC (Intergovernmental Panel on Climate Change; Box 1) as much as possible, because the IPCC has demonstrated success at moving complex science into the public arena, and directing global attention to a pressing environmental problem, despite large uncertainties and vocal opposition. The most important idea that the MA borrowed from the IPCC was the use of 'scenario analyses' or alternative plausible futures, used to highlight the consequences of societal choices.

Two additional hallmarks of the IPCC process that the MA adopted were the use of large international teams of authors and an exhaustive peer-review process. Altogether, 1360 scientists from 95 countries contributed to the production of MA's 13 volumes of conceptual framework, syntheses of existing conditions and trends, scenarios of possible ecosystem futures, and summaries for policy-makers. The reports were reviewed by 850 scientists and policy-makers from around the world, who collectively submitted 20 742 comments to which the authors responded. The MA attempted to inform crucial decisions by integrating ecological and socio-economic models at unprecedented scales and levels of conceptual comprehensiveness. It has influenced several international conventions and national governments [4], but much work remains before integrative ecological and socio-economic models will reach their full potential. Here, we review the models that formed the core of the MA scenario analyses (but not the scenarios themselves) and discuss what immediate scientific advances are needed to make such models compelling and widely used policy-making tools.

The MA models

The MA organized its scenario analyses around provisioning ecosystem services (food, fuel wood and fresh water), regulating services (air quality regulation, climate regulation and erosion), and supporting services (primary production and biodiversity). Scenarios were developed to anticipate responses of these services to alternative futures driven by different sets of policy decisions. The MA used scenario analyses that combined qualitative models (for factors such as technological innovation, social change and economic growth) and quantitative models (for water withdrawals, food supply, land-use change and species extinctions). Four plausible scenarios were created to address the uncertainty of the future, and to highlight tradeoffs between emphases on global cooperation versus unilateral economic growth, alternative types of technology development, and contrasting policy responses to poverty and environmental problems. Here, we describe the major quantitative models used in the MA scenarios and then turn to future modeling challenges.

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Box 1. The IPCC paradigm

The IPCC has had 18 years and three major global assessments to work out the kinks of global climate scenario analysis, and it shows. Their website (http://www.ipcc.ch/) is an incredible portal, providing access and clarity to anyone who is interested. The IPCC has made the structure of the models, the conditions of scenarios, and the data themselves available in ways that enable people of all skill levels to ask questions and draw their own conclusions.

First, the IPCC leaves no question about how well the models fit historic data. Reports and PowerPoint slides describing and illustrating the validation process are extensive. Second, the IPCC has made historic data, as well as data used for scenarios, available for the creation of maps and graphs, or for direct download. They have developed an online interface that enables users to produce global maps of historic levels or changes in several climate indicators, such as maximum temperature (Figure I). Users can also map the agreement between historic and modeled data and directly download any mapped data. All downloadable data are accompanied by technical guidelines for appropriate data use and interpretation.

These tools enable policy makers to visualize specific patterns and determine the changes that might be most important to them. They also help people understand the level of risk tied to outputs of various IPCC scenario analyses. Tools such as these for the MA would enable regional leaders to see how they measure up globally, and would then allow them to take a closer look using regional models with freely available data and models, or by adding their own.

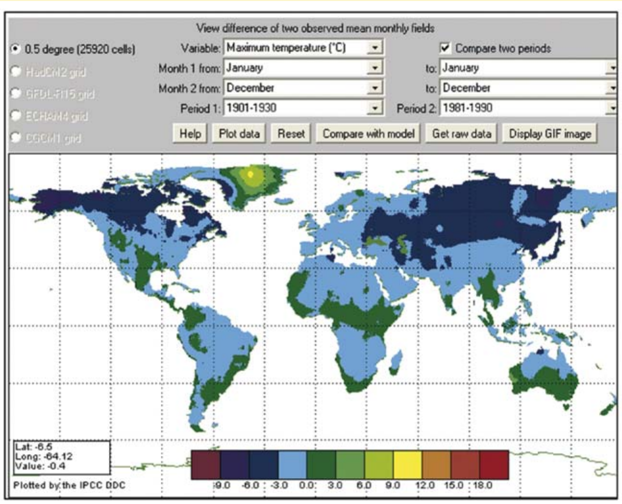

Figure I. The user interface for mapping and downloading data on the IPCC data portal. Historic data, modeled data and comparisons across time for many climate parameters are freely available in map or spreadsheet format (http://ipcc-ddc.cru.uea.ac.uk/java/visualization.html). Reproduced with permission from IPCC.

Modeling water

WaterGap, the Water-Global Assessment and Prognosis model, projects water supply and demand based on the natural water cycle (including climate, hydrogeology and land cover) and human water use (including irrigation, livestock, domestic and industrial uses) (Table 1) [5]. WaterGap has a global $0.5^\circ \times 0.5^\circ$ resolution and projects the total annual discharge of ~10 500 river basins. At the scale of individual watersheds, it is not considered reliable, but at the scale of entire river basins, WaterGap is capable of accuracy within 1–10% of observed discharges for long-term averages (assuming climate, land cover and use inputs are correct) [6]. In the demand side of the model, land cover is resolved only to the two crude categories of irrigated and non-irrigated land, but agricultural crops are specified to rice and non-rice categories because of the large difference in water needs.

In the MA, the main WaterGap drivers were climate, water withdrawal and water consumption. Climate came from IPCC models, and withdrawal and consumption were summed over agricultural, industrial and human drinking water demands according to either empirical relationships or presumed societal changes. Examples of empirical relationships were the amount of water needed to support a given number of livestock, with data on per animal livestock needs, or water needed per unit of produced electricity. Examples of presumed changes in society included different efficiencies in water use associated with shifts from thermal to non-thermal power plants, or from thirsty crops (rice) to crops that require less water (sorghum).

Modeling food

The International Food Policy Research Institute (IFPRI; http://www.ifpri.org) developed the IMPACT (International Model for Policy Analysis of Agricultural Commodities and Trade) model used by the MA to predict the supply, demand and prices for 32 agricultural commodities (Table 1) [7]. The commodities were cereals, soybeans, roots and tubers, meats, milk, eggs, oils, vegetables, fruits, sugar and fish, which account for most of the food production and consumption worldwide. Commodity projections were made using a set of 36 country- or region-level supply and demand equations that are meant to reflect a global market equilibrated by trade. Although climate variability does not directly influence agricultural yields in the model, it does influence land-cover changes, which, in turn, can modify commodity supply. The World Bank and UN have used IMPACT to make short-term predictions of the numbers of malnourished children expected year-by-year in developing nations [7].

A more recent version of the model, IMPACT-WATER, has been used to dissect and understand the regional impacts of the 'Green Revolution' from 1960 to 2000.

Table 1. Outputs and best available online resources for the primary models used in the MA

Model	General output	Website
IMPACT	% and number of malnourished children Supply, demand and prices for 32 agricultural commodities	http://www.ifpri.org/themes/impact.htm
IMAGE	Regional energy consumption and related emissions Terrestrial CO_2 and greenhouse gas fluxes Atmospheric greenhouse gas concentrations Transformation of land cover	http://www.ciesin.org/datasets/rivm/image2.0-home.html
WaterGap	Global water supply and global water demand	http://www.usf.uni-kassel.de/watclim/
Ecopath with Ecosim	Biomass estimates of multiple marine resource pools	http://www.ecopath.org

During this time, although global agricultural productivity was greatly enhanced through massive inputs of fertilizer and new varieties of crops, productivity gains were uneven across crops and regions, and many farmers failed to realize income gains [8]. These models can be powerful decision-making tools, but their accuracy needs to be tested.

Modeling land-use, energy and atmosphere

The IMAGE model, developed by the Dutch National Institute of Public Health and Environmental Protection (http://www.rivm.nl; Table 1), was designed to simulate the global society–biosphere–climate system at a spatial resolution of $0.5^\circ \times 0.5^\circ$ cells [9]. The model consists of three fully linked submodels: energy-industry, the terrestrial environment, and atmosphere–ocean. Its energy-industry submodel projects greenhouse gas emissions, given energy consumption and industrial production. Energy consumption is predicted from several economic and demographic factors in 13 world regions. In the terrestrial environment submodel, global land-cover change is driven by climate, economics and greenhouse gas fluxes. Finally, the atmosphere–ocean model links atmospheric greenhouse gas levels and the associated climate conditions (temperature and precipitation).

Together, these models give outputs for coarse-scale climate, regional energy consumption, greenhouse gas emissions, nitrogen deposition and land-cover change. Developers of the IMAGE model readily admit that only technical experts can use it, and that data documentation is poor. Making this model more available and transparent could have big payoffs because it has been verified against data from 1970 to 1990 and reliably reproduces major trends in regional energy use and emissions, greenhouse gas fluxes and land-use change [9].

Modeling biodiversity

Global models of biodiversity do not currently exist. This is not surprising, given that we are far from having an accurate global species inventory. Newspaper headlines reporting on the current extinction crises are typically based on somewhat 'hand-wavey' conversions of tropical deforestation rates to global losses of terrestrial species. Moreover, there are no quantitative models available for predicting changes in marine biodiversity. Hence, the best that the MA could do for marine species was to translate different types of fishing scenarios (e.g. harvests concentrated on high-value fish) into estimates of trophic diversity using the bioenergetic model, Ecosim. This model converts fishing pressure into cascading effects on trophic levels above and below that of the harvested fish (Table 1). In no way does it deal with questions of species loss.

We face similar shortcomings in freshwater habitats, where the MA relied on statistical relationships between river discharge and the number of fish species per river to predict freshwater species changes. The resulting predictions are highly suspect because discharge is not the only factor influencing fish diversity. For example, non-native species are a major source of extinction in aquatic systems, and most data on fish species per river do not distinguish between native and non-native species.

Box 2. The use of species-area curves to predict terrestrial extinction

The MA used species-area curves to project terrestrial biodiversity losses after habitat conversion because there is currently no alternative. However, mounting empirical evidence suggests that we should reconsider the predictive reliability of such curves.

Species-area curves relate species loss to habitat loss by assuming that the relationship between species diversity (S) and area (A) is described as $S = cA^z$, where c and z are fitted constants specific to particular taxa and habitats. Given this relationship, one can calculate how many species will go extinct with any incremental decrease in A. It appears simple and straightforward, but it is not. First, the expected species loss is strongly dependent on z, a parameter that varies so widely in nature and has such large confidence intervals that some ecologists have called predictions of extinction based on such equations 'specious' [23]. More importantly, applications of species-area curves to extinction predictions assume that any converted habitat is entirely inhospitable for all species, when it fact habitat conversion effects are rarely that dramatic. For example, Puerto Rican forest cover decreased by 99% between 1508 and 1900, yet only seven of 60 resident land bird species went extinct [24]. That negligible extinction rate would require a z value of 0.03, which is almost an order of magnitude less than the lower bound of the z values used in any of the MA scenarios or simulations (the MA based its predictions on z-values ranging between 0.25 and 0.81).

We cannot therefore continue to embrace species-area curves as a means of predicting global extinction. We need to revisit empirical studies recording local extinctions and build a theory that is more commensurate with the data. A new theory might attempt to predict the extinction of local or regional populations as opposed to global rates. Predictions at this scale would be more useful because ecosystem services and human well-being are not functions of the global species count, but rather respond to populations and their role in transferring energy and nutrients locally. A final advantage of building models of local extinction is that they could factor in other threats beyond habitat conversion, such as biological invasions or pollution.

We suggest that the best available knowledge for modeling changes in global freshwater and marine biodiversity is not sufficient to be included in any global assessments at this point. Continuing to report global predictions for freshwater and marine biodiversity trends gives the false impression that we have credible models for predicting species loss in these systems.

Global predictions of biodiversity loss are thus only feasible for terrestrial taxa. Within the terrestrial realm, species-area curves were used by the MA to generate rates of species loss based on the output from IMAGE (e.g. land-cover changes and habitat conversion). However, even the species-area approach to prediction of extinction has major weaknesses and has not been 'tested' in a satisfying manner (Box 2). The bottom line is that we lack a solid 'biodiversity science' that enables us to predict changes in global biodiversity as a result of alternative scenarios for human land-use and climate. By contrast, we might have sufficient scientific insight to predict local changes in biodiversity for selected taxa and habitats.

Linking the models

Unlike the IPCC with its central global general circulation models [10], the MA proceeded without a single, tightly integrated model. Instead, it relied on a loosely connected web of models that were fed the same common inputs

(Figure 1). The inputs, or drivers, were population growth, economic development, technology change, human behavior as it pertains to an emphasis on conservation, and the degree to which institutions promoted trade and technology transfer. Given these drivers, IMPACT calculated changes in agricultural production. IMAGE then took these outputs and calculated changes in land cover associated with changes in agricultural productivity. WaterGap generated river discharges assuming the land-uses and livestock production of IMAGE, as well as industrial and domestic water withdrawals associated with the drivers. Biodiversity changed as a result of land-use change, climate (which altered the 'area of biomes'), and nitrogen deposition, all of which are outputs of IMAGE.

The linking of the models was generally a one-way street where the output of one model was used as an input to another, precluding the possibility of certain feedback loops. For instance, there was no mechanism in the MA modeling approach for changes in land-use to feedback to disease outbreaks, even though several reviews of emerging human diseases cite this link as the most common factor underlying the transfer of diseases from wildlife to humans [11].

Scientific progress needed to make MA models more useful

There are three major technical shortcomings that limit the impact of the MA: (i) the absence of key feedbacks

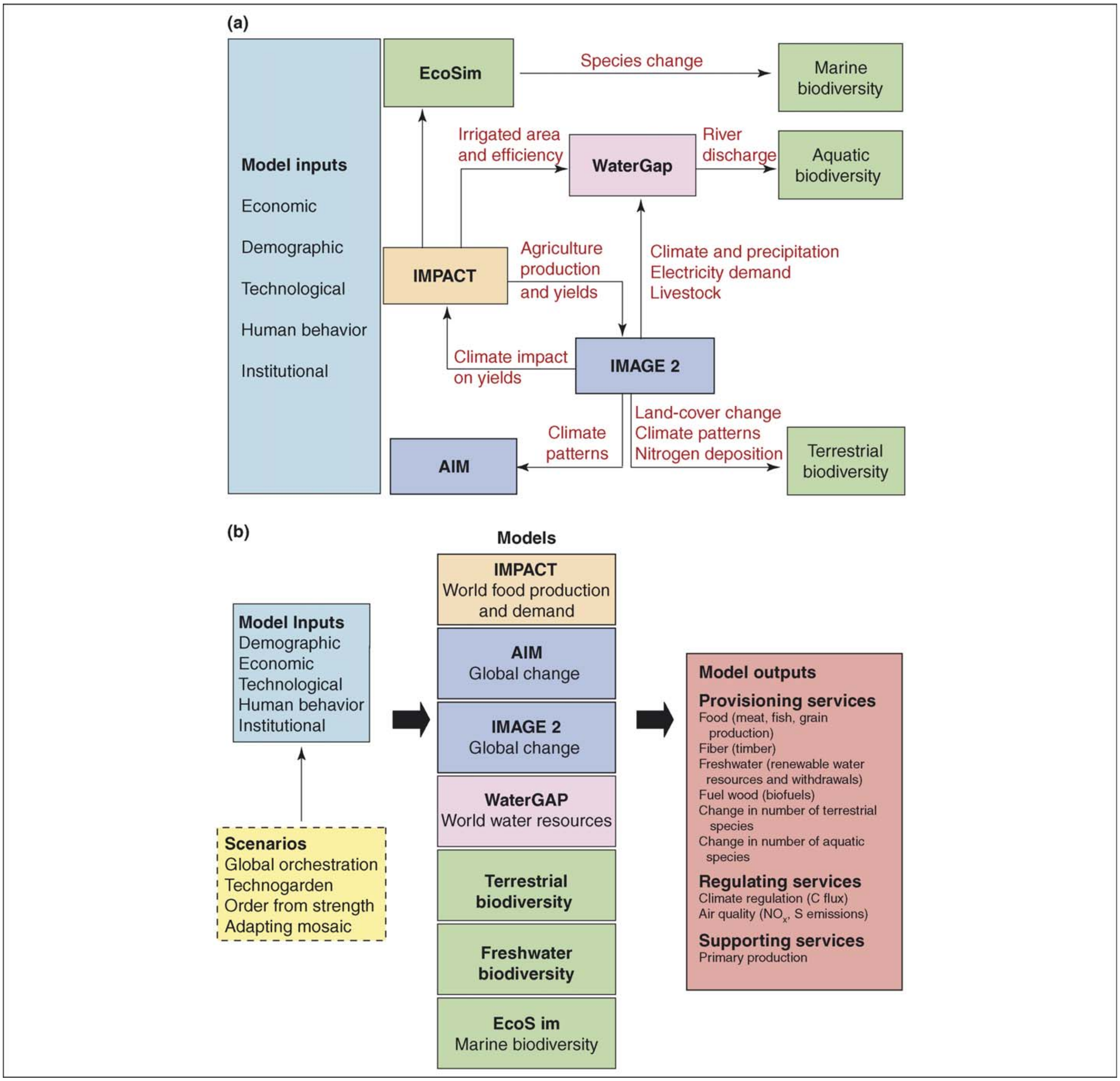

Figure 1. The general design of the MA model. **(a)** Inputs, or drivers, and outputs of the quantitative models used in the MA and **(b)** the framework for soft-linking these models **(b)**. There is a paucity of feedback loops, and it is recommended that future assessments should incorporate more feedbacks among models. (b) reproduced with permission from [25].

between model components; (ii) the inability to predict thresholds; and (iii) poorly documented connections between ecosystem services and human well-being.

Model feedbacks

The easiest of these shortcomings to address is better incorporation of feedbacks among model components. The MA was the first global model that included climate, demography, economics and ecology, and connecting these systems together was itself a Herculean challenge. Several research groups are already working to better incorporate feedbacks in linked models. For instance, a recent model couples ecosystem productivity and nitrogen cycling, yielding more accurate projections of carbon sequestration than do vegetation models that neglect nitrogen feedbacks [12].

Modeling thresholds

Identifying and modeling ecological thresholds were a focus of the MA modeling groups. This was no small task and, in general, the MA failed to document clear thresholds or develop theory capable of anticipating them. Even when we have data before and after major system changes, we still have little success in modeling thresholds. For instance, the IMPACT model fails to replicate the collapse of the Soviet Union, an event that dramatically changed demand and production trends. Thresholds are hard to model because few have been observed (but see [13] for a database of existing examples). We might have the best success in finding systems with thresholds by scaling up from the simple, mechanistic theories that we know include thresholds. For example, the threshold theorem of epidemiology shows that any disease relying on contact for transmission will have a threshold in its rate of spread [14]. Given this, we might first look for ecosystem service-human health thresholds in regions where contact-based communicable diseases are prominent. Similarly, we might expect thresholds to emerge in systems where herbivores or predators prefer competitively dominant species. In these systems, alterations in consumer density can shift the community between different states [15]. Although these mechanistic theories are highly simplified, they might lead us to important system thresholds more quickly than would an undirected search for thresholds.

Modeling social–ecological systems

Unlike modeling thresholds, we can make real progress in the short term towards defining relationships between human uses and ecosystem services. The key to rapid progress is the realization that decades of pertinent research have already been done by those in the resource-use community, although the phrase 'ecosystem services' was not largely adopted by the researchers [16–19]. For example, net primary productivity (NPP, known as yield to foresters) has been well studied under different land-use regimes and practices; with a brief literature review, 39 independent values for old-growth net primary production were found and 72 values for single-species tree plantations in the tropics. The distributions of these data show that carbon sequestration (as measured by NPP) is generally higher in tropical monoculture plantations than in tropical old-growth forests (Figure 2). Formal meta-analyses could be done on similar data for a whole list of ecosystem functions that are important to human well-being, such as soil fertility, soil retention, water provisioning, and so on. More difficult, but still possible, would be an extension to economics, so that yield, economic returns and market balance are measured simultaneously with ecosystem function [20].

Think globally, but act locally

The MA placed priority on communicating its findings to three international conventions; the Convention on Biological Diversity (CBD; http://www.biodiv.org/), the Ramsar Convention on Wetlands (http://www.ramsar.org/), and the Convention to Combat Desertification (CCD; http://www.unccd.int) [4]. In this arena, the MA has been largely successful, with conventions moving on MA findings within a year of completion of the general assessment. The CBD and Ramsar have taken steps to incorporate the MA

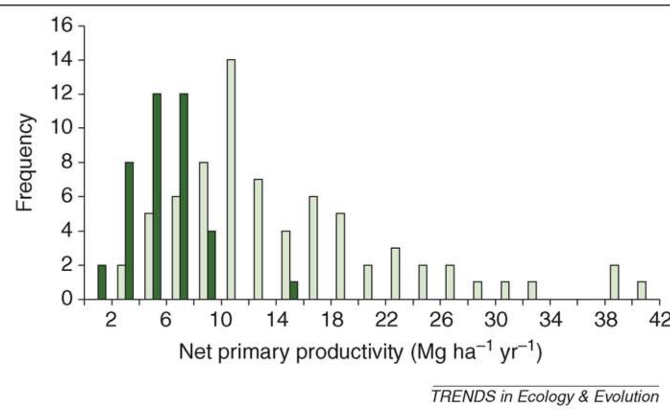

Figure 2. Distributions of literature values for net primary productivity in primary tropical forest (dark-green bars) and tropical monoculture tree plantations (light-green bars). Data were drawn from peer-reviewed publications in a brief literature review conducted by the authors. Monoculture plantations generally have higher rates of primary production, and thus higher rates of carbon sequestration, than do old-growth forests. Data such as these come primarily from the forestry and management literature as opposed to ecology journals and are not traditionally referred to as 'ecosystem services'. Nonetheless, they can be used to improve our models of interactions between ecosystem services, social decisions or policy incentives, and markets aimed at global vegetation cover. From the figure, it is clear that, when comparing topical monocultures with tropical primary forest, tropical monocultures sequester more carbon. Thus, a policy that was based only on carbon sequestration (or climate regulation) would not necessarily favor the preservation of primary forest in the tropics. The addition of other ecosystem services could change this decision.

process and findings into their own programs. The CCD has endorsed the MA, but has not yet translated MA findings into its decision language [4].

National, state and local governments have more power over real impacts on ecosystems than do international conventions and, in this realm, the MA has had less influence. We emphasize the importance of smaller-scale assessments because many of the serious threats to ecosystems and human well-being are mired in regional idiosyncrasies. For instance, a new rice paddi in Indonesia has different consequences for water quality than does one in Nigeria. Alternatively, a new car on the streets in New York City might have the same implications for global climate as one in Papua New Guinea, but the policy options for affecting climate change in the two places will have little in common.

Results of the MA such as '60% of the ecosystem services assessed are being degraded' are of little use to the general public or policy-makers, because they are interpreted as 'doom-and-gloom' sermons and are not easily associated with specific actions. To overcome this disconnect, the MA has several sub-global assessments underway, and their impacts are yet to be seen. It will be essential that these regional assessments get their messages across in sound bites that policy makers and the public can hear. An exemplary scenario analysis that did communicate its findings in a way that made a difference was a study of climate change impacts in California funded by the Union of Concerned Scientists (UCS; http://www.ucsusa.org/) [20].

The UCS study used a statistically downscaled version of two global circulation models to consider future emissions conditions for the state and produced compelling climate-related outputs [21]. Projections for the next century, in the absence of aggressive emissions regulations, included heat waves that would kill 165–330 additional people each year in Los Angeles, a shorter ski season, annual losses of US$266–836 million for the dairy industry, and bad-tasting wine from the Napa Valley. These kinds of findings resonate. The study was covered extensively by national and California newspapers, radio stations and TV stations, including CNN [22]. Winebusiness.com even carried an article; not your usual purveyors of such findings. Most importantly, California policy makers listened. Authors of the research presented findings in support of the Pavley Bill, now passed by the state legislature and expected to reduce California new car emissions 30% by 2016 (http://www.arb.ca.gov/cc/ab1493.pdf). The governors of neighboring states have followed suit, approving recommendations for action on climate change. Authors of the work have also spoken nationally and internationally (Dialogue on Future International Actions to Address Global Climate Change, hosted by Mexico, European Climate Forum; http://www.european-climate-forum.net). This is the kind of impact that the sub-regional MA projects and future assessments can, and should have.

Conclusion

The MA marks the emergence of ecology as a global science and its increasing integration with social sciences. Realizing the goal of the MA of ecologically informed decisions regarding energy, development and land-use options will require more than just academic research; it will require projects that effectively connect the science of ecosystem services with on the ground conservation or poverty alleviation. Three major institutions have already taken the plunge. Stanford University (http://www.stanford.edu/), the World Wildlife Fund (http://www.wwf.org) and The Nature Conservancy (http://www.nature.org) are developing projects that integrate ecosystem services with conservation [4]. We cannot expect our political leaders or the general populace to embrace the cautions and lessons of the MA or future assessments until we develop vivid demonstrations of improved human well-being as a result of improved ecosystem management.

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