

Global Change and Wilderness Science

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Abstract—The breadth and scope of human-caused environmental change is well-established; the distribution and abundance of species, the vegetation cover of the land, and the chemistry of the atmosphere have been altered substantially and globally. How can science in wilderness areas contribute to the analysis of human-caused change? We use nitrate losses from forests to evaluate this question. Determining the effects of past land-use change can be done straightforwardly; evaluating regional changes in the nitrogen cycle requires us to go farther in order to find useful comparisons; and no modern comparisons can contribute directly to understanding the possible effects of elevated atmospheric carbon dioxide.

Many species modify the environment they inhabit, but humanity does so more broadly, more pervasively and more intensively than does any other species. Human influences are not new—we have long reached into most areas of Earth—but the explosive growth of our population, resource use and commerce in the past few decades has multiplied our influence and expanded the facets of the Earth system that we modify. What can wilderness science contribute to our understanding of a changing Earth, and our influence on it? What does the term “wilderness science” mean on a rapidly changing Earth?

In this paper, we present a brief overview of some components of human-caused global change. We then discuss examples of how little-modified ecosystems can provide a baseline for understanding how the world works and for documenting human-caused change. Finally, we show that assuming that (apparently) little-modified ecosystems provide a baseline may be misleading; there is no true baseline left on Earth, no system that has escaped significant human influence.

Background

Much of the public discussion and debate concerning global environmental change has focused on changes in climate, particularly global warming. The focus on climate seems particularly strong in discussions of how humanity

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has affected and will affect wilderness—understandably so, since climate change does not respect the boundaries of designated wilderness areas. However, there is much more to global change than climate change, and some of the other components of change are better documented and, to date, and for some time to come, more important than climate change (Vitousek and others 1997c). Human-caused climate change will occur; it probably has started already (Intergovernmental Panel on Climate Change, 1996)—but it is only one of a large set of global changes.

We view global environmental change as illustrated in figure 1 (Vitousek and others 1997b). Growth in the size of and resource use by the human population is supported by a number of enterprises (agriculture, industry, trade) that alter aspects of the Earth system, including the composition of the atmosphere, the dynamics of the major biogeochemical cycles, land use and land cover, the transport of species to distant biogeographic regions and more. These direct changes in turn drive changes in global climate, by enhancing the greenhouse effect, and in Earth's biological diversity, most importantly through species extinction driven primarily by land use change. By and large, the direct effects of humanity are better documented and farther advanced than climate change or the loss of biological diversity.

Among these direct effects, the increasing concentration of carbon dioxide in the atmosphere perhaps provides the clearest signal of global change. Carbon dioxide has been

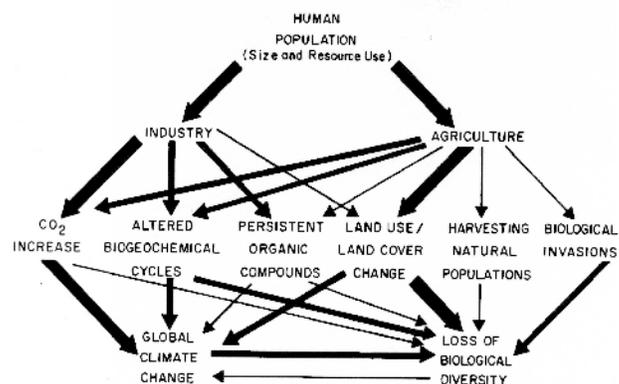


Figure 1—Components of human-caused global change. Growth in the size of and resource use by humanity entrains industrial and agricultural enterprises that drive a series of well-documented global changes, including alterations to atmospheric chemistry, the major biogeochemical cycles, land use, and the distributions and abundances of plant and animal populations. These changes in turn cause climate change and loss of biological diversity. From Vitousek and others (1997b).

measured directly since 1957; during that time it has increased monotonically (and at an accelerating rate) from ~315 to ~363 ppm (Intergovernmental Panel on Climate Change 1996). Moreover, analyses of air bubbles trapped in the Greenland and Antarctic ice caps extend the record back into the past. We can use this record to show that the concentration was close to stable near 280 ppm for several thousand years prior to about 1750, at which time it began an accelerating increase to the present.

On longer time scales, carbon dioxide in the atmosphere varies more substantially, with a relatively high concentration (~280 ppm) in interglacial times and a lower concentration (~195 ppm) during full-glacial times. However, the modern increase began at a high point and has increased outside of the range of concentrations over the past 400,000 years, at least. Some of the changes in the prehistoric record revealed in ice cores are fast—but the modern increase is ~10 times faster. Finally, the magnitude of the modern increase is already about as large as the full glacial/interglacial range—and there is no end to the increase in sight.

Carbon dioxide is an important greenhouse gas—it is transparent to incoming visible radiation but traps outgoing infrared—and its increasing concentration will drive climate change. There is uncertainty about how much change, and how fast, but not about whether there will be change. In addition, and perhaps more importantly, carbon dioxide is the basic raw material for photosynthesis. In most plants, rates of photosynthesis are not saturated at the current concentration in the atmosphere, and many experimental studies have demonstrated that an increased CO₂ concentration increases plant growth and often ecosystem-level productivity (DeLucia and others 1999, Hungate and others 1997). However, increased carbon dioxide affects species differently (Curtis and Wang 1998, Poorter 1993), stimulating some substantially (among them the invasive grass *Bromus tectorum* (Smith and others 1987)) and others very little. As a consequence, we must expect that competitive relationships among species will change systematically as carbon dioxide increases; there will be winners and losers among unmanaged as well as managed species.

At the same time, increased carbon dioxide generally decreases the quality/digestibility of tissue in those plants that respond most positively to it; such plants have lower protein and mineral concentrations when grown with increased carbon dioxide (Field and others 1992). Consequently, many herbivores are influenced by increased carbon dioxide; they must spend more time feeding to balance their protein budgets, and growth rates and survivorship often decrease, and the likelihood of predation increases in consequence (Fajer and others 1989). Overall, no plant, no animal on Earth is unaffected by increased carbon dioxide, which human activity already has increased ~30 percent over pre-industrial conditions.

Another significant global change is our alteration of the global cycle of nitrogen. The nitrogen cycle consists of a large, well-mixed reservoir of molecular nitrogen (N₂) in the atmosphere that is not available to most organisms and a slow, mostly biological transformation of that nitrogen into biologically available forms, in which the nitrogen is combined with carbon, hydrogen, or oxygen. This transformation, nitrogen fixation, is carried out by a range of bacteria and blue-green algae, some of which occur in symbiotic

associations with plant roots. Background rates of nitrogen fixation are relatively small on land, totaling about 100 million metric tons/year, and a low supply of fixed nitrogen limits the growth of many plants and ecosystems (Vitousek and Howarth 1991).

Humanity offsets N limitation through industrial fixation of nitrogen from the atmosphere (which now amounts to ~80 million tons/year), and through the cultivation of leguminous crops with nitrogen-fixing symbioses (such as soybeans and alfalfa, which contribute ~40 million tons/year). We also fix and mobilize nitrogen during fossil fuel combustion (~25 million tons) (Galloway and others 1995, Smil 1990, Vitousek and others 1997a). Altogether, our activities fix more N than all natural processes (on land) combined, and the change is surprisingly recent, in that more than half of all N fixed industrially in all of human history has been fixed in the past 15 years (Kates and others 1990, Vitousek and others 1997a).

Most of our fixation of nitrogen is for the benefit of agricultural productivity—and indeed the current human population could not be supported without the use of nitrogen fertilizer. However, nitrogen applied to agricultural systems does not stay where it is applied. Rather, it is transported as trace nitrogen gases through the atmosphere and deposited downwind, it moves in dissolved forms through soils to streams and groundwater, and it moves in agricultural produce through our transportation systems into us and thence (in wealthier societies) into sewage treatment plants.

Where fixed nitrogen is transported or deposited, it has many and varied effects on organisms and ecosystems. In estuaries and the coastal ocean, it drives eutrophication, enriching the productivity but decreasing the biological diversity of receiving waters, often leading to algal blooms, some of them noxious, and low-oxygen zones (Nixon and others 1996). On land, added nitrogen similarly increases the productivity but decreases the diversity of many ecosystems (Berendse and others 1993, Tilman 1987); it can also alter ecosystem functioning profoundly through a cascade of effects termed “nitrogen saturation.” These effects include the potential for acidification of soils and streams, and the development of nutrient imbalances and reduced growth rates in forests (Aber and others 1989, 1998; Fenn and others 1998).

Changes in carbon dioxide and in the global cycle of nitrogen are just two of the changes outlined in figure 1; we have described them briefly here because we will explore the implications of these particular changes (and their interactions) for wilderness science. The status of other components of human-caused global change is summarized in figure 2 (Vitousek and others 1997c). Not only has carbon dioxide increased ~30 percent and nitrogen fixation more than doubled as consequence of human activity—nearly half of the ice-free surface of Earth has been transformed by human activity (Daily 1995, Kates and others 1990), more than half of the accessible fresh water is utilized (Postel and others 1996), more than 20 percent of all wild plants in Canada (and many other places) are introduced from elsewhere (Rejmanek and Randall 1994), as many as a quarter of all bird species have been driven to extinction (Barbault and Sastrapradja 1995), and fully two-thirds of all marine fisheries are at their limit of exploitation or already are overexploited and declining (Food and Agricultural Organization 1994). These global changes are not some extrapolation to the future, they are

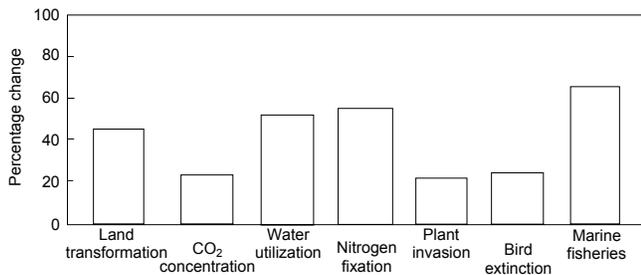


Figure 2—The current extent of human alteration of a number of major components of the Earth system. From Vitousek and others (1997c).

not the predictions of some model, they are not particularly controversial. They are known, and they are with us now.

Global Change and Wilderness Science

What does the extent and pervasiveness of human-caused environmental change imply for wilderness, and for wilderness science? If by “wilderness,” we mean areas of Earth that are unaffected by human activity, then there is no wilderness left on Earth; every place is affected by increased carbon dioxide and by one or more other changes. Given the history of human presence over most of Earth, and our effectiveness in exterminating or suppressing megafauna, there hasn’t been much wilderness in this sense for a long time. However, modern global change adds new dimensions of human influence across Earth.

On the other hand, we can array Earth’s ecosystems along a gradient from those influenced by distant (in space or time) human activities to those that are wholly dominated by humanity. Systems in which human effects have been relatively small, systems with less rather than more human influence, can then be used to identify and to understand some of the components of global change and their consequences.

We discuss several studies in which little-modified ecosystems have been used to provide a baseline against which the influence of anthropogenic changes can be evaluated. For all of these, we focus on the concentrations of fixed nitrogen, particularly nitrate, in streams that drain forested watersheds. The fixed nitrogen in small streams represents nitrogen that has been lost from forest; it thereby provides information on the ability of forests to retain nutrients. This nitrogen also has the potential to influence the dynamics of downstream ecosystems.

The first example is nitrate in streams draining forested watersheds in New England. In the 1970s, nitrate concentrations were low in streams draining forests that had been logged decades previously. These forests were still accumulating biomass, and nitrogen in that biomass, so nitrogen losses were less than atmospheric inputs of fixed nitrogen to those forests. In contrast, forests that had never been logged had much higher concentrations of nitrate in streams (Vitousek and Reiners 1975). These forests were no longer accumulating much nitrogen in growing biomass or in soils, so losses to streamwater were closer to the inputs of nitrogen

to these forests. Studies elsewhere in New England and the southern Appalachians yielded similar results (Martin 1979, Silsbee and Larson 1982).

More broadly, the forests that never had been logged could be used as a baseline for the others; with them, it was possible to see the legacy of human-caused land-use change, decades after the fact. More recent studies demonstrate that it is possible to trace these effects back nearly two centuries (Aber and Driscoll 1997). The comparison of baseline and human-modified ecosystems shows us something fundamental about the ways that forest ecosystems work and something important about the persistent consequences of a widespread component of global change.

It should be noted, however, that New England is downwind of the agricultural and industrial heartlands of the United States. All of New England is greatly affected by human alteration of the N cycle; atmospheric deposition of fixed nitrogen there is far above background levels, and far above the levels observed in more remote regions of Earth (Holland and others 1997). Do the substantial nitrate concentrations observed in streams draining never-logged New England forests reflect regional human alteration of the nitrogen cycle?

Hedin and others (1995) evaluated this question by measuring fixed nitrogen in the streams draining some temperate forests in Chile. Coastal southern Chile is among the least polluted areas of Earth with regard to anthropogenic nitrogen. The reactive nitrogen gases that contribute to deposition downwind of agricultural/industrial areas have fairly short residence times in the atmosphere (days), most such gases are emitted in the northern hemisphere, and southern Chile is remote even for the southern hemisphere; its rain sweeps in off the unbroken southern ocean.

Streams draining never-logged Chilean forests did not have high concentrations of nitrate; indeed, they had almost no nitrate at all (Hedin and others 1995). The main form of fixed nitrogen in these streams is dissolved organic nitrogen. Northern streams contain about as much dissolved organic nitrogen as these Chilean streams. However, in Chile, this loss of dissolved organic nitrogen may be sufficient to balance the very low inputs of nitrogen to these remote forests and perhaps sufficient to keep the supply of nitrogen to trees low enough to constrain forest growth. In contrast, the northern hemisphere systems are awash in anthropogenic fixed nitrogen, and they lose substantial quantities of nitrate as well as dissolved organic nitrogen (table 1).

In this case, the remote Chilean forests serve as a baseline, and the never-logged northern hemisphere forests (our previous baseline) are shown to be influenced substantially by human activity. It would be hard to characterize this human influence in New England without the little-modified southern hemisphere systems for comparison. Once again, this comparison teaches us something fundamental about how forest ecosystems work and something important about how they are altered by human activity.

So far so good. In both examples, we can use less modified systems to provide a baseline against which more modified systems can be evaluated. More recently, however, nitrate concentrations have been declining in streams draining New England forests — whether they have been logged or not (Aber and Driscoll 1997, Goodale 1999). Aber and Driscoll (1997) showed that while the long-term record of nitrate

Table 1—Nitrate concentrations (in $\mu\text{eq/liter}$) in streams draining forested watersheds. In each case, a human-altered situation is contrasted with a reference situation, in which human influence is considered to be smaller or absent.

| | Human-altered | Reference system | Citation |
|---|---------------|------------------|-------------------------------------|
| Case 1: Successional versus never-logged forests in New England in the 1970s. | 8 | 53 | Vitousek and Reiners 1975 |
| Case 2: Never-logged forests in New England versus Chile in the 1990s; Chile received much less anthropogenic N. | 17 | 0.1 | Hedin and others 1995, Goodale 1999 |
| Case 3: Never-logged forests in New England in the mid 1970s versus the mid 1990s; the effect of elevated CO ₂ could be greater in the 1990s. | 17 | 53 | Goodale 1999 |

losses from the intensively monitored Hubbard Brook Experimental Forest displays substantial year-to-year variability, nitrate concentrations could be predicted quite well by a model that incorporated year-to-year variations in climate. In the mid-1980s, though, observed concentrations fell consistently below predicted ones, and the difference widened in the 1990s. Similarly, the Bowl Natural Area, a never-logged forest near Hubbard Brook, had much lower nitrate concentrations in the mid-1990s than the mid-1970s. Streams in never-logged forests continued to have higher nitrate concentrations than those in forests logged decades ago, but nitrate concentrations in both have declined substantially (Goodale 1999).

What has caused this change? It is not caused by declining inputs of fixed nitrogen; these have been more or less constant. Other possible causes range from a rebound in forest growth following invasions by pests and pathogens to a change in forests or soils caused by declining inputs of sulfuric acid in precipitation. Another possibility is that the increasing concentration of carbon dioxide in the atmosphere has stimulated the growth of these forests, thereby increasing plant demand for nitrogen and other nutrients. We do not know what causes the decline in streamwater nitrate, but increasing carbon dioxide is a plausible cause (table 1).

If increased carbon dioxide is in fact responsible, there is no modern baseline against which this change can be evaluated. All of Earth is affected by it, no matter how remote. Similarly, all of Earth will be affected (though not equally) by climate change. Assuming again that carbon dioxide does cause the recent change in New England stream chemistry, we should worry a little about what our southern hemisphere baseline can tell us about nitrogen losses from never-logged forests. We have to recognize the possibility that the Chilean forests, measured initially in the 1990s, might have had slightly different dynamics earlier, before increased carbon dioxide stimulated their demand for nitrogen. Certainly they must have been very different from northern hemisphere forests that receive substantial anthropogenic nitrogen, then as now, but we could overstate the magnitude of that difference by missing the (assumed) effect of elevated carbon dioxide.

Conclusions

We conclude with three more or less contradictory thoughts about wilderness science in a changing world.

1. The world is changing substantially under human influences, and it will continue to be altered by human activity for the foreseeable future.

2. Nevertheless, the baseline represented by little-managed systems represents our best way of evaluating and understanding some of the major components of human-caused global change.

3. While we need to seek—and preserve and protect—systems that can provide a baseline for evaluating human-caused change, we should also be suspicious of what they can tell us. Indeed, we should be suspicious of the idea of a baseline in a changing world. Paleocological studies, rather than comparative studies, may provide a more direct baseline for evaluating change—at least in those characteristics of ecosystems that leave an interpretable record. We should not reject baseline studies or baseline ecosystems, but we should use them cautiously (table 1).

References

- Aber, J. D.; Driscoll, C. T. 1997. Effects of land use, climate variation, and N deposition on N cycling and C storage in northern hardwood forests. *Global Biogeochemical Cycles* 11: 639–648.
- Aber, J. D.; Nadelhoffer, K. J.; Steudler, P.; Melillo, J. M. 1989. Nitrogen saturation in northern forest ecosystems. *BioScience* 39: 378–386.
- Aber, J. D.; McDowell, W. H.; Nadelhoffer, K.; Magill, A.; Berntson, G.; Kamakea, M.; McNulty, S.; Currie, W.; Rustad, L.; Fernandez, I. 1998. Nitrogen saturation in temperate forest ecosystems: Hypothesis revisited. *BioScience* 48: 921–934.
- Barbault, R.; Sastrapradja, S. 1995. Generation, maintenance, and loss of biodiversity. In: Heywood, V. H.; Watson, R. T., eds. *Global Biodiversity Assessment*. U.N. Environment Program, Cambridge University Press: 197–274.
- Berendse, F.; Aerts, R.; Bobbink, R. 1993. Atmospheric nitrogen deposition and its impact on terrestrial ecosystems. In: Vos, C. C.; Opdam, P., eds. *Landscape Ecology of a Stressed Environment*. England: Chapman and Hall: 104–121.
- Curtis, P. S.; Wang, X. 1998. A meta-analysis of elevated CO₂ effects on woody plant mass, form, and physiology. *Oecologia* 113: 299–313.
- Daily, G. C. 1995. Restoring value to the world's degraded lands. *Science* 269: 350–354.
- DeLucia, E. H.; Hamilton, J. G.; Naidu, S. L.; Thomas, R. B.; Andrews, J. A.; Finzi, A. Lavine, M.; Matamala, R.; Mohan, J. E.; Hendrey, G. R.; Schlesinger, W. H. 1999. Net primary production of a forest ecosystem with experimental CO₂ enrichment. *Science* 284: 1177–1179.
- Fajer, E. D.; Bowers, M. D.; Bazzaz, F. A. 1989. The effects of enriched carbon dioxide atmospheres on plant-insect herbivore interactions. *Science* 243: 1198–1200.
- Fenn, M. E.; Poth, M. A.; Aber, J. D.; Baron, J. S.; Bormann, B. T.; Johnson, D. W.; Lemly, A. D.; McNulty, S. G.; Ryan, D. F.;

- Stottleyer, R. 1998. Nitrogen excess in North American ecosystems: predisposing factors, ecosystem responses, and management strategies. *Ecological Applications* 8: 706–733.
- Field, C. B.; Chapin, F. S. III; Matson, P. A.; Mooney, H. A. 1992. Responses of terrestrial ecosystems to the changing atmosphere: A resource-based approach. *Annual Review of Ecology and Systematics* 23: 201–235.
- Food and Agricultural Organization (FAO). 1994. *FAO Fisheries Technical Paper* 335.
- Galloway, J. N.; Schlesinger, W. H.; Levy, H. II; Michaels, A.; Schnoor, J. L. 1995. Nitrogen fixation: atmospheric enhancement—environmental response. *Global Biogeochemical Cycles* 9: 235–252.
- Goodale, C. L. 1999. The long-term effects of disturbance on nitrogen cycling and loss in the White Mountains, New Hampshire. University of New Hampshire, Durham, N.H.: Ph.D. dissertation. 145 p.
- Hedin, L. O.; Armesto, J. J.; Johnson, A. H. 1995. Patterns of nutrient loss from unpolluted, old-growth temperate forests: evaluation of biogeochemical theory. *Ecology* 76: 493–509.
- Holland, E. A.; Braswell, B. H.; Lamarque, J.-F.; Townsend, A.; Sulzman, J.; Muller, J.-F.; Dentener, F.; Brasseur, G.; Levy, H. II; Penner, J. E.; Roelofs, G.-J. 1997. Variations in the predicted spatial distribution of atmospheric nitrogen deposition and their impact on carbon uptake by terrestrial ecosystems. *Journal of Geophysical Research* 102: 15849–15866.
- Hungate, B. A.; Holland, E. A.; Jackson, R. B.; Chapin, F. S. III; Mooney, H. A.; Field, C. B. 1997. The fate of carbon in grasslands under carbon dioxide enrichment. *Nature* 388: 576–579.
- Intergovernmental Panel on Climate Change. 1996. *Climate Change 1995*. Cambridge, U. K.: Cambridge University Press
- Kates, R. W.; Turner, B. L.; Clark, W. C. 1990. The great transformation. In: Turner, B. L.; Clark, W. C.; Kates, R. W.; Richards, J. F.; Mathews, J. T.; Meyer, W. B., eds. *The Earth as Transformed by Human Action*. Cambridge University Press, England: 1–17.
- Martin, C. W. 1979. Precipitation and streamwater chemistry in an undisturbed forest watershed in New Hampshire. *Ecology* 60: 36–42.
- Nixon, S. W.; Ammerman, J. W.; Atkinson, L. P.; Berounsky, V. M.; Billen, G.; Boicourt, W. C.; Boyton, W. R.; Church, T. M.; Ditoro, D. M.; Elmgren, R.; Garber, J. H.; Giblin, A. E.; Jahnke, R. A.; Owens, N. P. J.; Pilson, M. E. Q.; Seitzinger, S. P. 1996. The fate of nitrogen and phosphorus at the land-sea margin of the North Atlantic Ocean. *Biogeochemistry* 35: 141–180.
- Poorter, H. 1993. Interspecific variation in the growth response of plants to an elevated ambient CO₂ concentration. *Vegetatio* 104/105: 77–97.
- Postel, S. L.; Daily, G. C.; Ehrlich, P. R. 1996. Human appropriation of renewable fresh water. *Science* 271: 785–788.
- Rejmanek, M.; Randall, J. 1994. Invasive alien plants in California: 1993 summary and comparison with other areas in North America. *Madrono* 41: 161–177.
- Silsbee, D. G.; Larson, G. L. 1982. Water quality of streams in the Great Smoky Mountains National Park. *Hydrobiologia* 89: 97–115.
- Smil, V. 1990. Nitrogen and phosphorus. In: Turner, B. L., II; Clark, W. C.; Kates, R. W.; Richards, J. F.; Mathews, J. T.; Meyer, W. B., eds. *The Earth as Transformed by Human Action*. Cambridge, U.K.: Cambridge University Press: 423–436.
- Smith S. D.; Strain, B. R.; Sharkey, T. D. 1987. Effects of CO₂ enrichment on four Great Basin grasses. *Functional Ecology* 1: 139–143.
- Tilman, D. 1987. Secondary succession and the pattern of plant dominance along experimental nitrogen gradients. *Ecological Monographs* 57: 189–214.
- Vitousek, P. M.; Reiners, W. A. 1975. Ecosystem succession and nutrient retention: a hypothesis. *BioScience* 25: 376–381.
- Vitousek, P. M.; Howarth, R. W. 1991. Nitrogen limitation on land and in the sea: How can it occur? *Biogeochemistry* 13: 87–115.
- Vitousek, P. M.; Aber, J. D.; Howarth, R. W.; Likens, G. E.; Matson, P. A.; Schindler, D. W.; Schlesinger, W. H.; Tilman, D. 1997a. Human alteration of the global nitrogen cycle: sources and consequences. *Ecological Applications* 7: 737–750.
- Vitousek, P. M.; D'Antonio, C. M.; Loope, L. L.; Rejmanek, M.; Westbrooks, R. 1997b. Introduced species: a significant component of human-caused global change. *New Zealand Journal of Ecology* 21: 1–16.
- Vitousek, P. M.; Mooney, H. A.; Lubchenco, J.; Melillo, J. M. 1997c. Human domination of Earth's ecosystems. *Science* 277: 494–499.