Global climate change and carbon management in multifunctional forests

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Fossil-fuel burning and deforestation have emerged as principal anthropogenic sources of rising atmospheric CO_2 and consequential global warming. Variability in temperature, precipitation, snow cover, sea level and extreme weather events provide collateral evidence of global climate change. I review recent advances on causes and consequences of global climate change and its impact on nature and society. I also examine options for climate change mitigation. Impact of climate change on ecology, economy and society – the three pillars of sustainability – is increasing. Emission reduction, although most useful, is also politically sensitive for economic reasons. Proposals of the geoengineering for iron fertilization of oceans or manipulation of solar flux using stratospheric scatters are yet not feasible for scientific and environmental reasons. Forests as carbon sinks, therefore, are required to play a multifunctional role that includes, but is not limited to, biodiversity conservation and maintenance of ecosystem functions; yield of goods and services to the society; enhancing the carbon storage in trees, woody vegetation and soils; and providing social and economic well-being of people. This paper explores strategies in that direction and concludes that the management of multifunctional forests over landscape continuum, employing tools of conservation biology and restoration ecology, shall be the vital option for climate change mitigation in future.

OBSERVED changes in temperature, precipitation, snow cover, sea level and extreme weather conditions confirm that the global warming is a reality. Scientific models and observations for the past 1000 years provide evidence that global warming is due to the anthropogenic increase in greenhouse gases (GHGs). Natural variability played only an ancillary role in the 20th-century warming[1,2].

Variability in earth's energy budget in the tropics, even without any obvious forcing, indicates that the earth's modes of variability may be more complex than understood[3–5]. Although average air temperature of the earth's surface has increased by 0.06°C per decade during the 20th century and by 0.19°C per decade during 1979–1998 (ref. 6), Antarctic continent has cooled by 0.7°C per decade between 1986 and 2000 with a corresponding decrease (6–9%) in primary productivity of lakes[7].

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Heat content of the world's oceans has increased over the last four decades, consistent with that expected from anthropogenic forcing[8], due mainly to increase of anthropogenic gases in the earth's atmosphere[9]. Mid-depth Southern Ocean temperatures have risen 0.17°C between the 1950s and the 1980s (ref. 2). This warming is faster than that of the global ocean and is concentrated within the Antarctic Circumpolar Current, where rates of change are comparable to increase in Southern Ocean atmospheric temperature[2].

Global surface air warming over the past 25 years has been ~ 0.5°C, and in the past century ~ 0.75°C. The second warmest global surface temperature was recorded in the 2001 meteorological year. It is different from the record warmth of 1998 that was heightened by a strong El Niño, which raised global temperature 0.2°C above the trend line[10].

Deforestation and climate change

Land-use change, ecological degradation, deforestation and biodiversity loss have emerged as major challenges for society[11–15]. Deforestation is a major anthropogenic climate-forcing agent, next only to fossil fuel-related emissions. Estimated net annual change in forest area globally in the 1990s was on the negative side, – 9.4 Mha (million ha), representing the difference between the estimated annual rate of deforestation of 14.6 Mha and the annual rate of increase in forest area of 5.2 Mha[16]. This was responsible for 20 to 25% of global anthropogenic GHG emissions during the 1990s, with the majority of deforestation occurring in the tropical regions.

Between 1850 and 1990, ~ 100 GtC (gigatonnes of carbon or 10^9 tonnes of carbon) was released into the atmosphere as a result of land-use changes[17]. The socio-economic factors associated with deforestation warrant that carbon conservation and carbon sequestration strategies will have to be integrated with biodiversity conservation and well-being of the people.

Projected global warming

If the mitigation policies are not translated in robust actions on the ground, the rate of warming will increase.

There are differing estimates of the range of warming due mainly to uncertainty in predictions models (Table 1). The Intergovernmental Panel on Climate Change (IPCC)[18] predicts that, under business-as-usual scenarios, mean temperatures worldwide will increase 1.4 to 5.8°C by 2100 as a result of growing GHG concentrations in the atmosphere. There are two more estimates comparable to IPCC estimates. Most recent among these suggests the warming at 5 to 95% confidence intervals to be 1.4 to 7.7 k (ref. 19) for a doubling of carbon dioxide in the atmosphere. Uncertainties still persist; all that can be said with any confidence concerning global warming is that the world has warmed during the past century and much of that warming is probably due to anthropogenic emission of GHGs into the atmosphere[20].

Tree-ring records are crucial for reconstructing coherent, large-scale, multicentennial temperature trends of the past. Temperature changes based on the tree-ring data suggest that climate swings in the last 1000 years were greater than IPCC estimates[21]. More studies are needed to know why the earth was once so warm and then so cool[22], before it can become certain if 21st-century warming projection is likely to be nearer to the top or the bottom of the projected range of 1.4 to 7.7°C (Table 1) of Forest *et al.*[19].

In India, ring-width chronologies of *Cedrus deodara*, *Pinus wallichiana* and *Picea smithiana* from the western Himalaya show absence of any warming trend in the 20th century[23]. But, in future, the situation is likely to be different. Revised trends for the principal anthropogenic forcing agents for the future suggest that the Indian subcontinent will experience an annual mean area-averaged surface warming in the range between 3.5 and 5.5°C during 2080s (ref. 24). Annual surface air temperature over Indo-Gangetic Plains has shown increasing trends up to 1958, but declined since, due mainly to expansion of irrigated agriculture[25].

Data and models both suggest that abrupt climate change during the last glaciation originated through changes in the Atlantic thermohaline circulation in response to small changes in the hydrological cycle[26]. Hydrological interaction between the Atlantic thermohaline circulation and adjacent continental ice sheet can trigger abrupt warming[27].

Table 1. Simulated range of global warming by 2100 for a doubling of atmospheric CO_2

Year and reference	Range of predicted warming (°C)	
	Minimum	Maximum
IPCC 1996 (ref. 103)	1.0	3.5
IPCC 2001 (ref. 18)	1.4	5.8
Wigley and Raper[104]	1.7	4.9
Forest *et al.*[19]	1.4	7.7

Impact of the changing climate on nature and society

Projected impacts from global warming include disruption of ecosystems, species extinctions, inundation of coastal areas due to rise in sea level, increasing precipitation and floods, and severe and frequent storms. As a consequence, ecology, economy and society – three segments of global and local sustainability – may likely suffer.

Positive feedback due to warming-induced CO_2 release is also predicted. Global warming just by 2°C is predicted to increase additional carbon release from soil by more than 10 PgC (petagrams or 10^{15}g of carbon) per year, resulting into more greenhouse effects and aggravating the anthropogenic warming[28]. Flux of current photosynthetic assimilates to roots by trees is a key driver of soil respiration[29].

India may experience between 5 and 25% decline in wintertime rainfall, leading to droughts during the dry summer months. On the other, projected increase in area-averaged summer monsoon rainfall over the Indian subcontinent[24] is only 10 to 15%. Summer monsoon rainfall has indeed increased over the Indo-Gangetic Plains during 1829–1999 and has shifted westward[25]. The dates of onset of summer monsoon over different parts of India would also become more variable.

Prolonged drought may result in population dislocation and redistribution, dwelling abandonment and state collapse[30,31]. For instance, archaeological and soil-stratigraphic data ascribe the climatic reasons for origin, growth and collapse of Subir, the third millennium rain-fed agriculture civilization of northern Mesopotamia on the Habur Plains of Syria[32]. Subsequent to a volcanic eruption in 2200 BC, a marked increase in aridity and wind circulation induced the land-use degradation in the region. After four centuries of urban life, such 'abrupt climatic change caused abandonment of Tell Leilan, regional desertion, and collapse of the Akkadian empire based in southern Mesopotamia'. There was a synchronous collapse in adjacent regions as well, suggesting that the impact of the abrupt climatic change was indeed extensive[32].

Climate change had a role in the collapse of the Maya civilization, which developed around 3000 years ago in Mesoamerica, and after flourishing during the Classic Maya period, it collapsed around 750–900 AD due to climate deterioration in the Maya region towards the end of the Classic period[33,34].

Effects of rainfall and drought in equatorial East Africa during the past 1100 years bear links with climate change and cultural effects. Both oral traditions and scientific evidence testify drought-induced famine, political unrest, and large-scale migration of indigenous peoples, and thereby establish strong links between cultural development and climate change[35].

Radiative effects of anthropogenic changes in atmospheric composition are also expected to cause an intensification of the global water cycle, with a consequent increase in flood risk[36–38]. For instance, Milly *et al.*[36] investigated the changes in risk of great floods – that is, floods with discharges exceeding 100-year levels from basins larger than 200,000 km^2 – using both stream-flow measurements and numerical simulations of the anthropogenic climate change associated with GHGs, and direct radiative effects of sulphate aerosols[36]. They found that the frequency of great floods increased substantially during the 20th century, and the trend will continue. There is also increase in probability of floods for the Asian monsoon region, with implications for flooding in Bangladesh[37].

The IPCC has noted that there is likely to be a net extension in the distribution of malaria and an increase in incidence in Africa[6]. But long-term meteorological trends in four high-altitude sites in East Africa, where increases in malaria have been reported in the past two decades, show that temperature, rainfall, vapour pressure and the number of months suitable for *Plasmodium falciparum* transmission have not changed significantly during the past century or during the period of reported malaria resurgence[39]. Therefore, claimed associations between malaria resurgences and regional changes in climate are not corroborated. The factors responsible for recent changes in malaria epidemiology in Africa are other than climate change.

Gradients of precipitation, temperature and soil fertility explain the global distribution of large herbivore diversity across the world, and help to identify crucial areas for conservation and restoration[40]. Wildlife populations would be affected by any change in factors that govern their distribution.

Increases in the prevalence of some of the biological invaders would alter basic ecosystem properties in ways that feed back to affect many components of global change. Experimental studies[41] have demonstrated that, under some circumstances, a short-term increase in water availability can facilitate the long-term establishment of alien plant species. Milchunas and Lauenroth[42] applied water, N and water plus N treatments to Colorado shortgrass steppe communities over five years. Sixteen years after treatments were halted, communities that had been supplemented with water had large populations of non-native species, whereas the control communities remained alien-free.

Effect of climate change in oceanic ecosystem functioning is poorly understood. There are indications, however, that climate change has caused an immediate accumulation of organic matter on the deep-sea floor, altered the carbon and nitrogen cycles, and has had negative effects on deep-sea bacteria and benthic fauna[43]. As deep seas cover over 50% of the surface of the earth and drive biogeochemical cycles on a global scale, such effects shall be crucial in future.

Effect of elevated levels of CO_2 on forests

Many studies provide the evidence of climate change[44–46] and its implication for terrestrial[47–52] and oceanic ecosystems[53,54] in India. There is also increasing global evidence to show that recent climatic and atmospheric trends are already affecting species physiology, distribution and phenology. The following situations are becoming progressively evident[55–57]:

- The extension of species' geographic range boundaries either towards the poles or to higher elevations.
- The extinction of local populations along range boundaries at lower latitudes or lower elevations.
- Increasing invasion by opportunistic, weedy and/or competitively mobile species.
- Progressive decoupling of species interactions (e.g. plants and pollinators) owing to mismatched phenology.

Since ecological boundaries of Indian forest types are defined by several climatic factors, projected climate change will affect the distribution and composition of Indian vegetation. Climate change will compound local anthropogenic factors, such as deforestation. Disturbance to ecosystems may bring changes of the magnitude not yet known in India[51]. Because of the complexity of local and global change, even if climatic conditions favour expansion, forest area is unlikely to expand; it may decrease in parts where deforestation and degradation are intense[52].

Elevated levels of CO_2 enhance growth rates and increase in the amount of nitrogen fixed symbiotically in *Acacia* species[58]. This provides an opportunity to plan for a species mix that maximizes the growth of multifunctional plantations.

Increasing levels of atmospheric CO_2 are expected to enhance the growth rate of trees. Current estimates of annual terrestrial plant uptake of carbon due to CO_2 fertilization are within the range $0.5–2.0 \times 10^{15}$ g, which is about 8–33% of annual fossil-fuel emissions[59]. In two forest experiments[60] on maturing pines exposed to elevated atmospheric CO_2, the CO_2-induced biomass carbon increment without added nutrients was undetectable at a nutritionally poor site, and the stimulation at a nutritionally moderate site was transient, stabilizing at a marginal gain after three years. Nevertheless, a large synergistic gain from higher CO_2 and nutrients was found with nutrient addition. The gain in productivity was larger at the poor site. Thus, soil fertility can restrain the carbon sequestration due to increased atmospheric carbon dioxide[60].

Under these circumstances, soil conservation measures to protect the top layer of the soil will be an important management strategy. As trees in poor soils give better response to elevated levels of CO_2, it will be a useful strategy to resort to large-scale restoration efforts in degraded forests and wasteland as a climate change mitigation option in the short-term.

Strategies for climate change mitigation

Emission reduction

Primary strategies to mitigate climate change effect are reduction of GHGs and carbon sequestration in oceans and terrestrial ecosystems. Reduction and stabilization of atmospheric GHG concentrations at a safe level is a paradigm that the scientific and policy communities have widely adopted for addressing the problem of climate change. However, because there is no determined or agreed safe level of GHGs in the atmosphere, the term 'safe level' has more of a socio-political connotation than scientific underpinning. The optimum that the society can strive to achieve is to bring the concentration of CO_2 and GHGs to pre-industrial (year 1750) level.

Reduction of emission from fossil fuels is definitely superior to sequestration of carbon because, apart from mitigating the climate change it also has health benefits. A mere 10% reduction of co-pollutants can avoid approximately 64,000 premature deaths, 65,000 chronic bronchitis cases, and 37 million person-days of restricted activity or work loss in four cities in USA alone[61] through 2020. Economic benefits of the Kyoto Protocol, however, are not perceived in the fear of reduced economic growth due to proposed cut in fossil-fuel use.

Maximum rate of global warming can be restricted to < 0.2°C/decade by restraining fossil-fuel emission rates during the present century to < 0.03 GtC yr^{-1}. However, if the known fossil-fuel reserve of ~ 4000 GtC is emitted, CO_2 will reach ~ 1000 ppmv and the earth will be warmed by > 5°C by the end of the millennium[62] (see Table 2 for total carbon pool in other systems).

Earth systems engineering (geoengineering)

The prospect of manipulation of solar flux using stratospheric scatterers may be sufficient to initiate an ice age at an annual cost of less than 0.01% of global economic output, but at the moment proposed geoengineering schemes for earth systems management have flaws[63,64], and it may take a long time to use research by the society.

Table 2. Carbon pool in major reservoirs on earth

Pool	Approximate quantity of carbon in Gt
Atmosphere	720
Ocean	38,400
Lithosphere: sedimentary carbonate	> 60,000,000
Lithosphere: kerogen	15,000,000
Terrestrial biosphere	2200
Aquatic biosphere	1–2
Fossil fuel	4130

Modified after ref. 105.

Another geoengineering proposal[63,65] to fertilize oceans by adding large quantities of iron to increase phytoplankton bloom, could remove large amounts of CO_2 from the atmosphere[66]. Fertilizing the 'biological pump' may thus enhance the flux of carbon into the oceans[63]. There are problems, however. Even if iron fertilization was used to the extent possible, the carbon flux would not exceed ~ 1 GtC per year[63]. Such efforts, either through iron fertilization programmes[67] or through CO_2 injection into the deep sea may not be viable, even if CO_2 is first reacted with water and carbonates to form dissolved bicarbonate for release into the ocean[68]. It may affect the sea biota in ways currently unknown to science. Analysis on how such deep-sea disposal of CO_2 may affect organisms living in these environments, caution that even small perturbations in CO_2 or pH may have significant consequences for deep-sea ecosystems and for global biogeochemical cycles[69,70]. Iron fertilization would be extremely difficult to validate and would significantly alter oceanic food webs and biogeochemical cycles[67]. Pending the detailed studies in this aspect, multifunctional forest management emerges as a crucial climate change mitigation option.

Storage of carbon in world's forests

The storage of carbon depends on CO_2 fixation through photosynthesis and the release of carbon as CO_2 through the respiratory activities of plant roots, their symbiotic mycorrhiza fungi, soil microbes and micro-fauna, and anthropogenic release of CO_2 due to deforestation, forest harvest, grazing and burning.

Ability of forests, trees and other vegetation as terrestrial carbon sinks to absorb CO_2 emissions and mitigate the climate change, has attracted wide attention. Currently, total above-ground biomass in the world's forests is 421×10^9 tonnes distributed over 3869 Mha. Of this, 3682×10^6 ha or 95% is natural forest, and 187×10^6 ha or 5% is plantation area. On an average, forests contain 100 m^3 ha^{-1} (cubic metre per ha) wood volume, and 109 t ha^{-1} (tonne per ha) wood biomass. Forests store 1200 GtC in vegetation and soil globally. Carbon in forests constitutes 54% of the 2200 Gt of the total carbon pool[16] in terrestrial ecosystems. Forests sequester 1 to 3 GtC annually through the combined effect of reforestation, regeneration, and enhanced growth of existing forests, offsetting the global CO_2 emissions from deforestation[71]. Carbon has also been absorbed by vegetation managed under ethnoforestry practices in landscape continuum across Asia, occurring in combination with rainwater harvesting and agroforestry systems.

As discussed earlier, growth of vegetation is also in response to environmental change-induced longer growing seasons, and fertilization by rising carbon dioxide in the atmosphere and nitrogen deposition in the soil.

In terms of global carbon cycle, nearly 120 PgC is exchanged in each direction between terrestrial ecosystems and the atmosphere, and another 90 PgC between the ocean and atmosphere annually[72].

The IPCC special report[73] on Land-Use, Land Use Change and Forestry (LULUCF) has noted that through suitable management regimes, the rate of sequestration could be enhanced up to 1.6 PgC yr^{-1} by the year 2010. Results of six dynamic global vegetation models[74] project that the terrestrial sink, excluding deforestation, will increase to ~ 5 PgC/yr by 2050, and then level-off or may decline. Simulations[74] with changing CO_2 alone show a widely distributed terrestrial carbon sink of 1.4–3.8 PgC yr^{-1} during the 1990s, rising to 3.7–8.6 PgC yr^{-1} after 100 years. Simulations that included climate change point out that as a result of the impacts of climate change on tropical and southern-hemisphere ecosystems, there will be a reduced sink both at present (0.6–3.0 PgC yr^{-1}) and a century later (0.3–6.6 PgC yr^{-1})[74].

A recent and most comprehensive analysis on global patterns of carbon exchange, by Schimel and colleagues[75] (Table 3), has substantiated that terrestrial and marine environments are currently absorbing about half of the carbon dioxide that is emitted by fossil-fuel combustion. Terrestrial biosphere was neutral with respect to net carbon exchange during the 1980s, but became a net carbon sink in the 1990s. The reasons have been attributed to sinks in North America and Eurasia. The tropics were just in balance with respect to carbon exchange, strengthening the case that emissions due to tropical deforestation are being offset by tropical tree-growing[75] (see also Table 3).

Northern high-latitude forests are assumed to be large sinks. But, reduced white spruce growth observed in Alaska is likely to be an important factor in future CO_2 uptake in the boreal forest. The current assumption of carbon-cycle models, of a uniform positive relationship of atmospheric carbon uptake to high-latitude warming, may lead to an overestimate of high-latitude carbon storage and an underestimate of future atmospheric carbon dioxide[60].

The global ocean sink is projected[75] to increase from the current 1.7 ± 0.5 PgC yr^{-1} to around 5 PgC yr^{-1} by 2100 (see Table 3). The land is now a net sink of 1.4–0.7 PgC per year[75,76]. Since deforestation is considered to be a source of 1.6 PgC/yr, the forests protected against deforestation must be a sink of 2 to 4 PgC per year[76]. Estimates of surface–atmosphere CO_2 fluxes from an intercomparison of atmospheric CO_2 inversion models, which include 16 transport models and model variants, found an uptake of CO_2 in the southern extratropical ocean less than that estimated from ocean measurements[77].

The role of the world's forests, ethnoforestry, and agroforestry systems as a sink for atmospheric carbon dioxide is the subject of active research and discussion. Long-term monitoring of plots in mature, humid tropical forests concentrated in South America revealed that biomass gain by tree growth exceeded losses from tree death in 38 of 50 Neotropical sites. These forest plots accumulated 0.71 ton, plus or minus 0.34 ton, of carbon per hectare per year during 1990s. The data suggest that Neotropical forests are significant carbon sinks[78]. However, a re-analysis[79] suggests otherwise, and found mean biomass change for these sites to be only 0.3 Mg ha^{-1} yr^{1} (megagrams or 10^6 grams per ha per year).

Other studies[80] suggest that tropical forests are useful sinks for decades to centuries. Data related to tropical-forest sample plots, which are maintained globally, are of useful quality. There is evidence to show that there has been a recent increase in the biomass in old-growth tropical forests[80].

Carbon in wood products

In addition to direct sequestration, some carbon will also remain locked in the wood that is put to non-emitting use. For instance, in the year 1998 the world consumed at least 1.75×10^9 m^3 of fuel-wood, 1.52×10^9 m^3 of industrial roundwood, and 0.17×10^9 tonnes of pulp for paper[16], apart from sawnwood, wood-based panels, paper and paperboard that may overlap with other categories. At

Table 3. Global patterns of annual carbon exchange in terrestrial ecosystems (PgC)

Exchange type	1980s[#]	1990s[#]	2100 Projections
(i) Emission (fossil–fuel burning, cement manufacture)	5.4 ± 0.3	6.3 ± 0.4	Uncertain; Reduced use of fossil fuel/technological innovations in energy sector can bring emission down.
(ii) Atmospheric increase	3.3 ± 0.1	3.2 ± 0.1	Depends on (i) and (iv)
(iii) Ocean–atmosphere flux	– 1.9 ± 0.5	– 1.7 ± 0.5	Uncertain
(iv) Land–atmosphere flux	– 0.2 ± 0.7	– 1.4 ± 0.7	Uncertain
(v) Emission due to land–use change	1.7 (0.6 to 2.5) (0.4 by tropical deforestation*)	1.6 ± 0.7	Halting deforestation, and sustainable management of multifunctional forests to increase sink capacity
(vi) Residual terrestrial sink	– 1.9 (– 3.8 to 0.3)	– 2 to – 4 (uncertain)	– 3.7 to – 8.6** (uncertain)

Source: [#]Schimel *et al.*[75] modified.
*Detwiler and Hall[106].
**Cramer *et al.*[74].

least some of this wood, excluding fuelwood, will remain locked for several years. About 90% of the total carbon harvested from Indian forests is released into the atmosphere within a year due to use as fuel-wood. A 0.8% remains locked in the wood products at the end of 100 years[81]. Compared to fossil fuels, use of wood fuel is less damaging to the environment.

Indian forests as carbon sinks

The amount of carbon stored in Indian soils is 23.4–27.1 Gt, which is 1.6 to 1.8% of the carbon stored in the world's soils[82,83]. The total soil organic C pool in Indian forests is 4.13 PgC in the top 50 cm and 6.81 PgC in the top 100 cm soil depth. The historic loss in forest soil organic C pool (1880–1981) in the top 100 cm soil depth has been estimated as 4.13 PgC (ref. 84).

Total above-ground and below-ground biomass in Indian forests has been estimated as 6865.1 and 1818.7 Mt, contributing 79 and 21% to the total biomass respectively[85]. The mean biomass density is 135.6 t ha^{-1}. The above-ground and below-ground allocation of biomass is in agreement with the Enquist–Niklas model[86], that predicts the allocation patterns of biomass partitioning in seed plants. Data (6865.1 and 1818.7) were plugged into the original data set of the Enquist–Niklas model, to see if these values for above-ground and below-ground biomass fall on the same regression curve as the original data. They do fit remarkably on the curve (ref. 86, pers. commun.).

Often it has been opined that forests in India are emitting more carbon compared with carbon sequestered by tree growth, and that this will remain so until there exists an alternative supply of timber and fuelwood. However, in the face of several studies, this view does not hold.

For the reference year 1986 gross emission from deforestation in that year, plus committed emissions from deforestation in the preceding years, has been estimated to be 64×10^6 tC in India[87]. But, there was no net emission because natural regeneration, forest succession and plantation sequestered the equivalent carbon[87]. Thus, the forest sector in India was in balance in terms of carbon. The situation has further improved in subsequent years.

The rate of afforestation in India is one of the highest among the tropical countries. The annual productivity has increased from 0.7 m^3 ha^{-1} in 1985 to 1.37 m^3 ha^{-1} in 1995. The carbon pool for the Indian forests has been estimated to be 2026.72 Mt for the year 1995 and annual carbon uptake at least 0.125 Gt of CO_2 from the atmosphere in that year[88]. Further, mitigation of about 3.32 Gt in the next 50 years at an annual reduction of about 0.072 Gt of carbon[89] is possible.

The situation has indeed improved further and the rate of deforestation is below the rate of afforestation. Area under forests in India remained stable at around 64×10^6 ha during the period 1986 to 1994. India is afforesting at an average gross rate of 1.55×10^6 ha yr^{-1} over the past ten years, while the gross deforestation rate was 0.272×10^6 ha yr^{-1} during this period[90]. When the net loss in forest area is considered, the annual deforestation rate was 100,750 ha during 1987–89; it declined in the subsequent years to less than 26,000 ha and increased to 274,100 ha annually during 1995–97 (ref. 90). But a comparative position of forest cover between 1997 and 1999 assessment by the Forest Survey of India[91] suggests that there is a net increase in the forest cover by 3896 km^2. Proposals of sustainable forestry scenario may enhance an additional carbon stock of 237×10^6 MgC during 2000 to 2012, and in addition to meeting all the incremental biomass demands of the nation, commercial forestry would lead to an additional carbon stock of 78×10^6 MgC during 2000 to 2012 under the commercial forestry scenario[90].

Enhancing carbon sink in multifunctional forests

Conference of Parties (CoP) of Kyoto Protocol in their sixth meeting (CoP6) decided to implement policies related to LULUCF to slow greenhouse warming.

We need to design silvicultural systems for multifunctional forests that are able to fulfil ecological, economic and social functions. This can be achieved with an innovative management regime that optimizes multiple-use benefits along with resistance and resilience of forests to climate change[92,93]. Such a management regime would need to address social, economic and ecological aspects, along with a multiple-use multi-stakeholder system applicable across landscape continuum (Table 4). All forms of ethnoforestry practices, production and protection forestry, and community management regimes[91,94–96] with their inherent social, economic and environmental benefits[97,98] could be the best mechanisms, provided that efforts to reduce emissions from fossil fuel are not given a back seat. Multifunctional forest management offers a suitable regime as it addresses the issues on all aspects of sustainability. Such management systems can also help address the socio-economic factors related to tropical deforestation[99]. Additionally, management systems that operate on landscape continuum rather than habitat-islands, provide an effective framework for integration of indigenous knowledge with formal science to achieve sustainability.

Holistic strategies for multifunctional forest management across landscape continuum should combine habitat restoration along with the application of conservation biology principals, to generate additional benefits such as climate-change mitigation, biodiversity conservation, and maintaining the ecosystem functions. Context-specific application of restoration and conservation strategies may vary depending upon the ecological elements of the countryside. Severely disturbed or impacted areas may require more of restoration science, whereas more natural and

Table 4. Management guidelines for multifunctional forests in landscape continuum

Key function	Consolidated key management guidelines*
Biodiversity conservation and maintenance of ecosystem functions	Representation of all forest types in protected areas[107], both formal[108,109] and ethnoforestry regimes. Protection of natural forests against wild-fires, grazing and unmanaged removals[107]. Priority protection to threatened ecosystems such as tropical dry forests. Preventing fragmentation and providing connectivity to conserve biodiversity in landscape continuum. Fragmentation of natural forests has a sequential path that starts with killing of big trees[110] followed by degeneration of habitat specialists, paucity of regeneration due to impoverished seed germination in fragments[111], and ends in denuded areas (Figure 2).
Yield of goods and services to the society	Maintenance of gene pool diversity in natural and cultural landscapes. Restoration of degraded forests with multiple-use trees, shrubs and herbs along with regeneration regimes that necessarily combine rainwater harvest[112], direct seeding, resprouting and plantations, if needed.
Enhancing the carbon storage in trees, woody vegetation and soil	Maintenance of woody vegetation in ethnoforestry regimes in landscape continuum (households, cultural landscapes, agroecosystems and wilderness)[98]. Protection to a variety of woody vegetation management regimes in agroecosystems to maximize social and economic benefits to the people as well as maintenance of ecosystem functions such as natural pest control, pollination, carbon storage, regulation of hydrological cycle, etc.[113].
Social and economic well-being of people	Only low intensity logging followed by matching regeneration in secondary forests[107] and ethnoforestry regimes[98]. Protection of the functional groups of biodiversity[114]. Protection to large trees in natural, cultural and human-modified landscapes, as they act as seed source, conserve carbon pool and act as habitat for seed-dispersing birds, small mammals and other faunal species[115,116]. Soil conservation and enhancement of soil fertility[117] through conservation/restoration[118–120] of woody leguminous species[121] across landscape continuum. Application of the principles of sustainability science[122] for forest management[92] attempting to address the nature–society interaction will need an interdisciplinary approach as well as multiple stocks of knowledge and institutional innovations to navigate transition towards a sustainable forest management. Application of conservation and restoration principles to community-based management regimes[123,124] built on the principle of equity of knowledge among stakeholders[125], that rely capitalizing on natural recovery mechanisms will prevent further catastrophic shift and degradation and retain the multiple values of land[126–129].

*The management guidelines appear in consolidated form because specific guidelines serve the cause of multiple functions. For example, the management guideline 'representation of all forest types in protected areas' serves to the cause of all the identified functions.

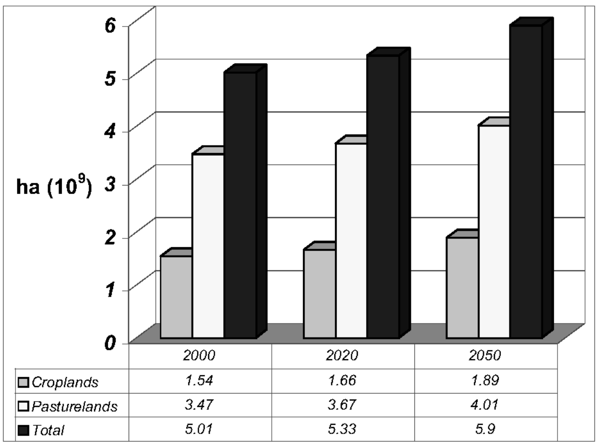

Figure 1. Potential global availability of area for tree-growing in croplands and pasturelands in the year 2000, 2020 and 2050. (Source: Ref. 101, data from ref. 102).

less disturbed areas may require more of conservation science. Thus, a basket of strategies has to be designed for the landscape continuum.

In addition, primary and secondary forests, and trees growing in agroforestry systems can continue to act as sinks even beyond the rotation age, if the harvest is accompanied by regeneration. The efficacy can further be improved if sequestered carbon is locked through non-destructive (non-CO_2 emitting) use of such wood.

The harvest in managed production systems outside natural reserves accompanied by regeneration can be scientifically planned in such a way that stand is harvested and regenerated just when the current annual increment (CAI) is either stagnant or no longer enough to provide sufficient mitigation benefits. Thus, the new crop of regenerating trees will start acting as sinks again.

Indeed, one billion people in India and a growing world population that may reach 10 billion by 2100, are expected to consume wood and non-wood products at substantial rates annually. The demand can only be met by regular harvest followed by regeneration in managed secondary forests and trees in agroforestry systems.

Even when the wood is used for CO_2-emitting applications, the emission will still be less than the comparable use of fossil fuels. Indeed, if the current biofuels were to

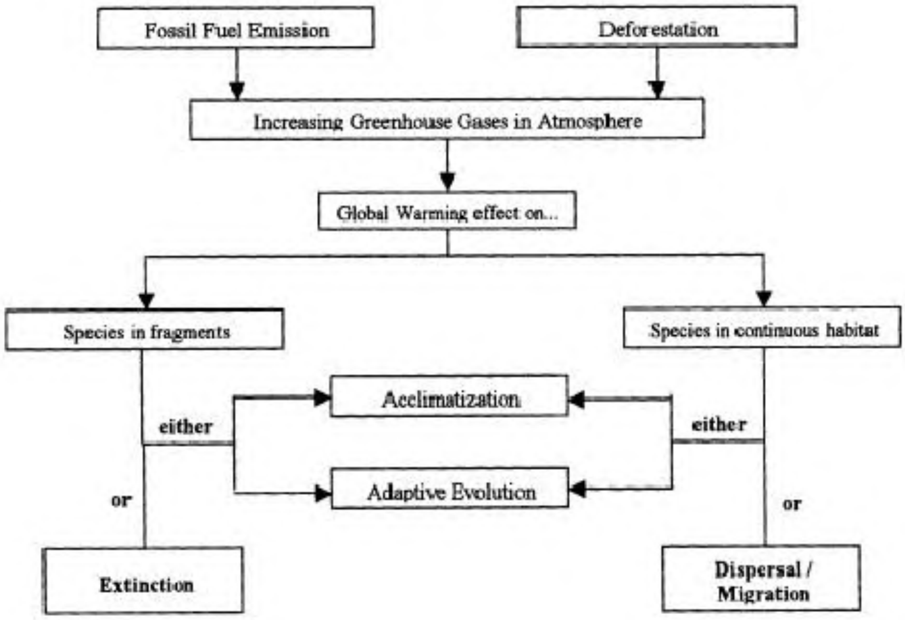

Figure 2. Importance of prevention of fragmentation and providing corridors for the survival of species in a warming world.

be replaced by fossil-fuels, additional carbon would reach the atmosphere annually. By promoting the use of wood fuel, we can avoid this additional emission. The global wood production amounts to 3.5 billion $m^3 yr^{-1}$, that leads to a net sink of carbon of 139 TgC y^{-1} (teragrams or 10^{12} grams carbon per year), as the production is larger than the decay of the wood products manufactured earlier[100].

In addition, not all the harvested wood may be put for CO_2-emitting uses. The harvested wood may be used in ways beneficial to sink activities: non CO_2-emitting uses such as furniture and construction; low CO_2-emitting uses such as fuelwood and/or biofuels. Linking the tree growing in agroecosystems and bioenergy options with CDM can further maximize benefits from the terrestrial carbon sinks[101]. Activities that reduce dependence on fossil fuels through product substitution will be an important component of the Kyoto Protocol. LULUCF activities can yield more biomass and thereby reduce dependence on fossil fuels. Such activities can also supply wood to manufacture products that can substitute for other products that have energy-intensive production processes.

Agroforestry systems can sequester carbon at time-averaged rates of 0.2–3.1 tC $ha^{-1} yr^{-1}$, though the rates can be as high as 10 tC $ha^{-1} yr^{-1}$ (ref. 73). A global potential can be projected based on the recent forecasts on agricultural expansion[102]. By the year 2050, land use is projected to reach 529×10^6 ha as irrigated agriculture, 1.89×10^9 ha as croplands and 4.01×10^9 ha as pastures. If the past trends continue, global croplands may increase by a net of 3.5×10^8 ha and pastures by 5.4×10^8 ha by the year 2050. By then, the combined total represents an 18% larger average global agricultural land base than at present[102]. We can guide our efforts simultaneously for saving the biodiversity and generating ecosystem services such as carbon sequestration. Tilman *et al.*[102] suggest that the 1.4×10^8 ha projected removal of land from agriculture in developed nations could be restored to conserve biodiversity, yield water and provide carbon sequestration benefits. Harnessing the potential of agroforestry systems for carbon sequestration is particularly important under such circumstances (ref. 101, Figure 1).

Conclusion

Global climate change has emerged as a serious challenge for sustainability. Carbon management in multifunctional forests assumes a great significance for climate-change mitigation, enhancing the yield of goods and services for the people and maintaining biodiversity and ecosystem functions. Multifunctional forest management requires novel approaches in order to maintain the resilience and usefulness of tropical forests. We have to provide increased support for management of secondary forests, restoration of degraded lands, plantation forestry in agroecosystems, management for the non-wood forest products, modifying the natural resource accounting procedures to reflect the true value of tropical forests, and support for forestry agencies and local communities in charge of forest protection (Table 4).

Long-term carbon management can be deliberately enhanced through suitable management regimes. Management of multifunctional forests offers opportunity for carbon sequestration, biodiversity conservation, and benefits to society. The policies and programmes have to address the landscape continuum. Management of multifunctional forests needs to draw both on conservation biology and restoration ecology (see Table 4 and Figure 2 for detailed suggestions). With appropriate management inputs, forests and vegetation in landscape continuum can support biodiversity conservation and maintenance of ecosystem functions, yield of goods and services, enhanced storage of the carbon to mitigate global climate change, and enhance social and economic well-being of the people.

1. Crowley, T. J., *Science*, 2000, **289**, 270–277.
2. Gille, S. T., *Science*, 2002, **295**, 1275–1277.
3. Wielicki, B. A. W. *et al.*, *Science*, 2002, **295**, 841–844.
4. Chen, J., Carlson, B. E. and Del Genio, A. D., *Science*, 2002, **295**, 838–841.
5. Hartman, D. L., *Science*, 2002, **295**, 811–812.
6. McCarthy, J. J., Canziani, O. F., Leary, N. A., Dokken, D. J. and White, K. S. (eds), *Climate change 2001: Impacts, Adaptation, and Vulnerability – Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, 2001.
7. Quayle, W. C. *et al.*, *Science*, 2002, **295**, 645.
8. Barnett, T. P., Pierce, D. W. and Schnur, R., *Science*, 2001, **292**, 270–274.
9. Levitus, S. *et al.*, *Science*, 2001, **292**, 267–270.
10. Hansen, J., Ruedy, R., Sato, M. and Lo, K., *Science*, 2002, **295**, 275.
11. Jha, C. S., Dutt, C. B. S. and Bawa, K. S., *Curr. Sci.*, 2000, **79**, 231–238.
12. Srivastava, S., Singh, T. P., Singh, H., Kushwaha, S. P. S. and Roy, P. S., *Curr. Sci.*, 2002, **82**, 1479–1484.
13. Joshi, P. K., Singh, S., Agarwal, S. and Roy, P. S., *Curr. Sci.*, 2001, **80**, 941–947.
14. Singh, J. S., *Curr. Sci.*, 2002, **82**, 638–647.
15. May, R. M., *Curr. Sci.*, 2002, **82**, 1325–1331.
16. *State of the World's Forests 2001*, Food and Agriculture Organization of the United Nations, Rome, Italy, 2001, p. 181.
17. Houghton, R. A., *Tellus B*, 1999, **51**, 298–313.
18. Houghton, J. T. *et al.* (eds), *Climate Change 2001: The Scientific Basis*, Cambridge University Press, 2001.
19. Forest, C. E., Stone, P. H., Sokolov, A. P., Allen, M. R. and Webster, M. D., *Science*, 2002, **295**, 113–117.
20. Kerr, R. A., *Science*, 2002, **295**, 29–31.
21. Esper, J., Cook, E. R. and Schweingruber, F. H., *Science*, 2002, **295**, 2250–2253.
22. Briffa, K. R. and Osborn, T. J., *Science*, 2002, **295**, 2227–2228.
23. Yadav, R. R., Park, W. K. and Bhattacharyya, A., *Quat. Res.*, 1997, **48**, 187–191.
24. Lal, M. *et al.*, *Curr. Sci.*, 2001, **81**, 1196–1207.
25. Singh, N. and Sontakke, N. A., *Clim. Change*, 2002, **52**, 287–313.
26. Clark, P. U., Pisias, N. G., Stocker, T. F. and Weaver, A. J., *Nature*, 2002, **415**, 863–869.
27. Schmittner, A., Yoshimori, M. and Weaver, A. J., *Science*, 2002, **295**, 1489–1493.
28. Luo, Y., Wan, S., Hui, D. and Wallace, L. L., *Nature*, 2001, **413**, 622–625.
29. Högberg, P. *et al.*, *Nature*, 2001, **411**, 789–792.
30. deMenocal, P. B., *Science*, 2001, **292**, 667–673.
31. Polyak, V. J. and Asmerom, Y., *Science*, 2001, **294**, 148–151.
32. Weiss, H. *et al.*, *Science*, 1993, **261**, 995–1004.
33. Hodell, D. A., Curtis, J. H. and Brenner, M., *Nature*, 1995, **375**, 391–394.
34. Webster, D., *The Fall of the Ancient Maya: Solving the Mystery of the Maya Collapse*, Thames and Hudson, New York, 2002, p. 368.
35. Verschuren, D., Laird, C. R. and Cumming, B. F., *Nature*, 2000, **403**, 410.
36. Milly, P. C. D., Wetherald, R. T., Dunne, K. A. and Delworth, T. L, *Nature*, 2002, **415**, 514–517.
37. Palmer, T. N. and Räisänen, J., *Nature*, 2002, **415**, 512–514.
38. Schnur, R., *Nature*, 2002, **415**, 483–484.
39. Hay, S. I. *et al.*, *Nature*, 2002, **415**, 905–909.
40. Olff, H., Ritchie, M. E. and Prins, H. T., *Nature*, 2002, **415**, 901–904.
41. Dukes, J. S. and Mooney, H. A., *Trends Ecol. Evol.*, 1999, **14**, 135–139.
42. Milchunas, D. G. and Lauenroth, W. K., *Ecol. Appl.*, 1995, **5**, 452–458.
43. Danovaro, R., Dell'Anno, A., Fabiano, M., Pusceddu, A. and Tselepides, A., *Trends Ecol. Evol.*, 2001, **16**, 505–510.
44. Rao, U. R. and Chakravarty, S. C., *Curr. Sci.*, 1992, **62**, 469–478.
45. Singh, J. and Yadav, R. R., *Curr. Sci.*, 2000, **79**, 1598–1601.
46. Gupta, P. K. *et al.*, *Curr. Sci.*, 2001, **80**, 186–196.
47. Farooqui, A. and Vaz, G. G., *Curr. Sci.*, 2000, **79**, 1484–1488.
48. Gadgil, S., *Curr. Sci.*, 1995, **69**, 649–659.
49. Parthasarathy, N., *Curr. Sci.*, 2001, **80**, 389–393.
50. Singh, J. S., Singh, L. and Pandey, C. B., *Curr. Sci.*, 1991, **61**, 477–480.
51. Meher-Homji, V. M., *Curr. Sci.*, 2000, **78**, 1–2.
52. Ravindranath, N. H. and Sukumar, R., *Clim. Change*, 1998, **39**, 563–581.
53. Arthur, R., *Curr. Sci.*, 2000, **79**, 1723–1729.
54. Ravindran, J., Raghukumar, C. and Raghukumar, S., *Curr. Sci.*, 1999, **76**, 233–237.
55. Hughes, L., *Trends Ecol. Evol.*, 2000, **15**, 56–61.
56. McCarty, J. P., *Conserv. Biol.*, 2001, **15**, 320–331.
57. Walther, G.-R. *et al.*, *Nature*, 2002, **416**, 389–395.
58. Schortemeyer, M., Atkin, O. K., McFarlane, N. and Evans, J. R., *Plant Cell Environ.*, 2002, **25**, 567–579.
59. Schimel, D. S., *Global Change Biol.*, 1995, **1**, 77–91.
60. Oren, R. *et al.*, *Nature*, 2001, **411**, 469–472.
61. Cifuentes, L., Borja-Aburto, V. H., Gouveia, N., Thurston, G. and Davis, D. L., *Science*, 2001, **293**, 1257–1259.
62. Lenton, T. M. and Cannell, M. G. R., *Clim. Change*, 2002, **52**, 255–262.
63. Keith, D. W., *Nature*, 2001, **409**, 420.
64. Keith, D. W., *Annu. Rev. Energy Environ.*, 2000, **25**, 245–284.
65. Schneider, S. H., *Nature*, 2001, **409**, 417–421.
66. Frost, B. W., *Nature*, 1996, **383**, 475–476.
67. Chisholm, S. W., Falkowski, P. G. and Cullen, J. J., *Science*, 2001, **294**, 309–310.
68. Rau, G. H. and Caldeira, K., *Science*, 2002, **295**, 275.
69. Seibel, B. A. and Walsh, P. J., *Science*, 2001, **294**, 319–320.
70. Seibel, B. A. and Walsh, P. J., *Science*, 2002, **295**, 276.
71. Malhi, Y. *et al.*, *Plant Cell Environ.*, 1999, **22**, 715–740.
72. Prentice, I. C. *et al.*, *IPCC Third Assessment Report 2001*, Cambridge University Press, 2001, vol. 1, pp. 183–237.
73. Watson, R. T. *et al.*, *IPCC Special Report on Land Use, Land Use Change and Forestry*, Cambridge University Press, UK, 2000.
74. Cramer, W. *et al.*, *Global Change Biol.*, 2001, **7**, 357–373.
75. Schimel, D. S. *et al.*, *Nature*, 2001, **414**, 169–172.
76. Scholes, R. J. and Noble, I. R., *Science*, 2001, **294**, 1012–1013.
77. Gurney, K. R. *et al.*, *Nature*, 2002, **415**, 626–630.
78. Phillips, O. L. *et al.*, *Science*, 1998, **282**, 439–442.
79. Clark, D. A., *Ecol. Appl.*, 2002, **12**, 3–7.
80. Phillips, O. L. *et al.*, *Ecol. Appl.*, 2002, **12**, 576–587.
81. Gundimeda, H., *Environ Dev. Sust.*, 2001, **3**, 229–251.
82. Gupta, R. K. and Rao, D. L. N., *Curr. Sci.*, 1994, **66**, 73.
83. Rastogi, M., Singh, S. and Pathak, H., *Curr. Sci.*, 2002, **82**, 510–517.

84. Chhabra, A., Palria, S. and Dadhwal, V. K., *For. Ecol. Manag.*, 2002, (5877, PII: S0378-1127(02)00016-6).
85. Chhabra, A., Palria, S. and Dadhwal, V. K., *Biomass Bioenergy*, 2002, **22**, 187–194.
86. Enquist, B. J. and Niklas, K. J., *Science*, 2002, **295**, 1517–1520.
87. Ravindranath, N. H., Somashekhar, B. S. and Gadgil, M., *Clim. Change*, 1997, **35**, 297–320.
88. Lal, M. and Singh, R., *Environ. Monitor. Assess.*, 2000, **60**, 315–327.
89. Singh, R. and Lal, M., *Curr. Sci.*, 2000, **78**, 563–567.
90. Ravindranath, N. H., Sudha, P. and Rao, S., *Mitig. Adapt. Strateg. Global Change*, 2001, **6**, 233–256.
91. *State of Forest Report 1999*, Forest Survey of India, Dehra Dun.
92. Pandey, D. N., *Conserv. Ecol.*, 2002, **6**, r13; [online] URL: http:// www.consecol.org/vol6/iss1/resp13.
93. Noss, R. F., *Conserv. Biol.*, 2001, **15**, 578–590.
94. Ravindranath, N. H., Pandey, D. N., Murthy, I., Bist, R. and Jain, D., *Communities and Climate Change* (ed. Poffenberger, M.), CFI, Santa Barbara, USA, 2001, pp. 1–73.
95. Pandey, D. N., *J. Bombay Nat. Hist. Soc.*, 1991, **88**, 284–285.
96. Pandey, D. N., *Indian For.*, 1993, **119**, 521–529.
97. Pandey, D. N., *Beyond Vanishing Woods: Participatory Survival Options for Wildlife, Forests and People*, Himanshu/CSD, New Delhi, 1996, 2 edn, p. 222.
98. Pandey, D. N., *Ethnoforestry: Local Knowledge for Sustainable Forestry and Livelihood Security*, Himanshu/AFN, New Delhi, 1998.
99. Bawa, K. S. and Dayanandan, S., *Nature*, 1997, **386**, 562–563.
100. Winjum, J. K., Brown, S. and Schlamadinger, B., *For. Sci.*, 1998, **44**, 272–284.
101. Pandey, D. N., *Climate Policy*, 2002, **2**, (in press).
102. Tilman, D. *et al.*, *Science*, 2001, **292**, 281–284.
103. Houghton, J. T. *et al.* (eds), *Climate Change 1995, Contribution of Working Group I to the Second Assessment Report of IPCC*, Cambridge University Press, 1996.
104. Wigley, T. M. L. and Raper, S. C. B., *Science*, 2001, **293**, 451–454.
105. Falkowski, P. *et al.*, *Science*, 2000, **290**, 291–296.
106. Detwiler, R. P. and Hall, C. A. S., *Science*, 1988, **239**, 42–47.
107. Bawa, K. S. and Seidler, R., *Conserv. Biol.*, 1998, **12**, 46–55.
108. Khoshoo, T. N., *Curr. Sci.*, 1996, **70**, 205–214.
109. Pandey, D. N., Measures of Success for Sustainable Forestry, World Bank-WWF Global Alliance for Forest Conservation and Sustainable Use; IIFM, Bhopal, 2001, p. 125.
110. Laurance, W. F., Delamônica, P., Laurance, S. G., Vasconcelos, H. L. and Lovejoy, T. E., *Nature*, 2000, **404**, 836.
111. Bruna, E. M., *Nature*, 1999, **402**, 139.
112. Pandey, D. N., *Science*, 2001, **293**, 1763.
113. Daily, G. (ed.), *Nature's Services: Societal Dependence on Natural Ecosystems*, Island Press, Washington DC, 1997.
114. Loreau, M. *et al.*, *Science*, 2001, **294**, 804–808.
115. Chambers, J. Q., Higuchi, N. and Schimel, J. P., *Nature*, 1998, **391**, 135–136.
116. Jipp, P., Nepstad, D., Cassle, K. and Carvalho, C. R., *Clim. Change*, 1998, **39**, 395–412.
117. Sanchez, P. A., *Science*, 2002, **295**, 2019–2020.
118. Janzen, D. H., *Science*, 1998, **279**, 1312–1313.
119. Bullock, J. M., Pywell, R. F., Burke, M. J. W. and Walker, K. J., *Ecol. Lett.*, 2001, **4**, 185–189.
120. Pandey, S. K. and Shukla, R. P., *Curr. Sci.*, 2001, **81**, 95–102.
121. Drinkwater, L. E., Wagoner, P. and Sarrantonio, M., *Nature*, 1998, **396**, 262–265.
122. Kates, R. W. *et al.*, *Science*, 2001, **292**, 641–642.
123. Getz, W. M. *et al.*, *Science*, 1999, **283**, 1855–1856.
124. Nepstad, D. *et al.*, *Science*, 2002, **295**, 629–631.
125. Pandey, D. N., *Conserv. Biol.*, (in press).
126. Daily, G. C., *Science*, 1995, **269**, 350–354.
127. Scheffer, M., Carpenter, S., Foley, J. A., Folke, C. and Walker, B., *Nature*, 2001, **413**, 591–596.
128. Dobson, A. P., Bradshaw, A. D. and Baker, A. J. M., *Science*, 1997, **277**, 515–522.
129. Gadgil, M., *Curr. Sci.*, 1982, **51**, 547–550.

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