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Estimating terrestrial net primary productivity over India using satellite data

Net primary productivity (NPP) is the fundamental process in biosphere functioning and is needed for assessing the carbon balance at regional and global scales. Changes in NPP could arise due to anthropogenic effects and climate change, and directly affect human and animal food supplies. Terrestrial NPP is one of the most-modeled ecological processes with models that differ markedly in approach and complexity, often yielding comparable global estimates[1]. With the availability of space-based Remote Sensing (RS) measurements providing global coverage with nearly daily sampling and techniques to estimate absorbed photosynthetically active radiation (APAR), the use of RS data has become the most preferred technique for estimating global NPP[2].

The terrestrial NPP of India, its quantum, spatial variability, and distribution across seasons is not well understood. Some preliminary estimates have been made as part of terrestrial carbon cycle assessment, viz. 1.24 $PgCa^{-1}$ [$Pg = 10^{15}$ g] for 1980 (ref. 3), and 1.32–1.59 $PgCa^{-1}$ for mid-eighties[4]. Recently, SPOT-VEGETATION data in the form of 10-day global NDVI (Normalized Difference Vegetation Index) composites have been used with C-Fix model to compute PAR and NPP at 1 km scale (http://www.geo-success.net). These NPP outputs from the C-Fix model have been used for arriving at country-wise estimates of African and European continents and also validated by comparing the model outputs with field measurements for two Euroflux test sites[5,6]. The C-Fix model calculates NPP by simulating carbon exchange using the following equation[7]:

NPP = uptake of carbon by photosynthesis – autotrophic respiration losses by vegetation

$$= S*c*\mathrm{fAPAR}*\varepsilon*p(T)*\mathrm{CO_2fert}*(1-r) \quad (\mathrm{mgC/m^2/day}), \qquad (1)$$

where S is the daily incoming global solar radiation [$MJ/m^2/d$]; c is the climatic efficiency 0.48, fAPAR is the fraction of adsorbed PAR estimated from RS-based NDVI, ε is the photosynthetic efficiency 1.10 [gC/MJ(APAR)], $p(T)$ is normalized temperature dependency factor (value between 0 and 1), and CO_2 fert is normalized CO_2 fertilization factor (dimensionless), and r is the fraction of assimilated photosynthates consumed by autotrophic respiration; modeled as simple linear function of daily mean air temperature.

We report here estimates of monthly net C fixation and net primary productivity over India and its eight regions, using SPOT-VEGETATION 10-day NPP composites, and comparing the monthly patterns of NPP and NDVI. Although many studies use calendar year for reporting

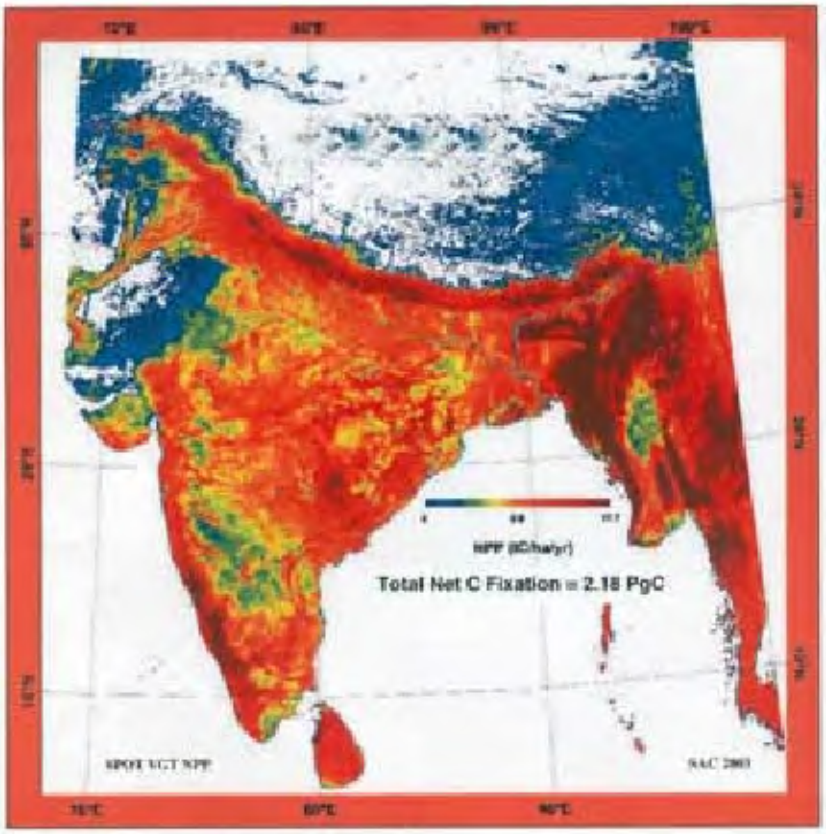

Figure 1. Net Primary Productivity Image over Indian sub-continent for June 1998–May 99 (using C-Fix model and SPOT VEGETATION 10-day NPP composites).

NPP, we have adopted an agriculture year (June 1998–May 1999) to better represent the effect of monsoon and the role of agroecosystem in controlling NPP over India. The preprocessing of data included reprojection of the original dataset from geographic coordinates to Albers Equal Area Projection using ENVI 3.5 Image Processing software and computing per pixel and regional NPP. Since the model input of fAPAR is derived from NDVI, the monthly profiles of SPOT NDVI 10-day composites were also analysed to compare the seasonal patterns of NPP and NDVI. NPP and NDVI were also separately estimated for eight geographic regions (with geographic area as per cent of India's total geographic area in parentheses) namely, Central (22.5%), East (12.9%), Islands (0.20%), Northwest (11.4%), Northeast (7.7%), Peninsular (19.5%), Western Region 1 (10.5%), and Western Region 2 (15.1%).

Using the Geographic Information System (GIS) layer of state/union boundaries, net carbon fixation of each region and mean NPP for each 10-day composite was computed. The total net C fixation of India was estimated as 2.18 PgC, which amounts to area-weighted terrestrial NPP of 6.66 $tCha^{-1} yr^{-1}$ for the period June 1998–May 1999. The integrated image from thirty six 10-day composites of modeled NPP over India for June 1998–May 1999 is shown in Figure 1. Indian landmass with 1.45% of the world's total geographical area accounts for approximately 2.7–5.5% to the global NPP estimates, which range from 40 to 80 PgC[8]. The regional contributions to the total net C fixation are—Central: 543.8 (24.9%), East: 314.6 (14.4%), Islands: 5.62 (0.3%), Northwest: 131.2 (6.0%), Northeast: 276.7 (12.7%), Peninsular: 483.9 (22.2%), Western Region 1: 109.4 (5.0%), and Western Region 2: 317.9 (14.6%) TgC (TgC = 10^{12} gC).

The detailed analysis has yielded a few surprising results about monthly and regional variations in net carbon fixation and NPP. Of the total annual net carbon fixation of 2.18 PgC, the contribution of June 1998 was minimum at 72.4 TgC, while February 1999 contributed a maximum of 280.5 TgC. These correspond to monthly NPP of 0.22 tC/ha/month in June 1998 and 0.86 tC/ha/month in February 1999. The estimated monthly variations in total net C fixation for different regions during June 1998–May 1999 are shown in Figure 2*a*. The month of peak net carbon fixation varies across regions, viz. January 99 for Peninsular region, February 99 for Central and Western region 1 and March 99 for North West region. In the Central region, net C fixation increased by 157% during August 98–February 99. In the Western region 2, there was a steady increase of net C fixation during June–December 98, followed by a slow decrease till May 99. The annual NPP in the natural vegetation dominated Northeast region was 10.9 tC/ha/yr as compared to only 3.50 tC/ha/yr for the agriculturally dominant Northwest region, respectively.

The seasonal patterns of NPP are controlled by incident PAR and absorbed PAR, since the latter is derived from NDVI; the monthly patterns of NPP and NDVI show relation between fAPAR and NPP. These patterns for Northeast and Northwest regions, Punjab state and India representing forest and agroecosystem regions, agriculturally rich state and subcontinent average, respectively are shown in Figure 2*b*. The estimated monthly NDVI was in the range of 0.32–0.75 and 0.18–0.32 in the northeast and northwest regions, respectively. The total annual NPP in the agriculture rich Northwest state of Punjab was estimated as 8.66 tC/ha/yr with nine-fold monthly variations. Due to irrigated agriculture in Punjab, the NPP and NDVI curves for Punjab are biomodal, as compared to the unimodal curves in other regions. For Punjab, the highest monthly NPP was estimated in March due to peak vegetative growth of crops, which suddenly drops to the lowest in May as a result of harvesting of winter crops. However, there were only 3.5 fold variations in estimated monthly NDVI in Punjab. An earlier study using RS-based approach and NOAA-AVHRR data had estimated the total agricultural NPP of 3.7 tC/ha for India[9]. Among the Indo-Gangetic plains states of India, high NPP of 7.6 tC/ha/yr was estimated for Punjab for 1991 using crop statistics based approach. This was anthropogenically controlled as it correlated high crop NPP with fertilizer application across years and between states[10]. The ratio of terrestrial phytomass to NPP is in the range of 1.5–2.5 for India[3,4,11], which is low as compared to 9–12 for global esti-

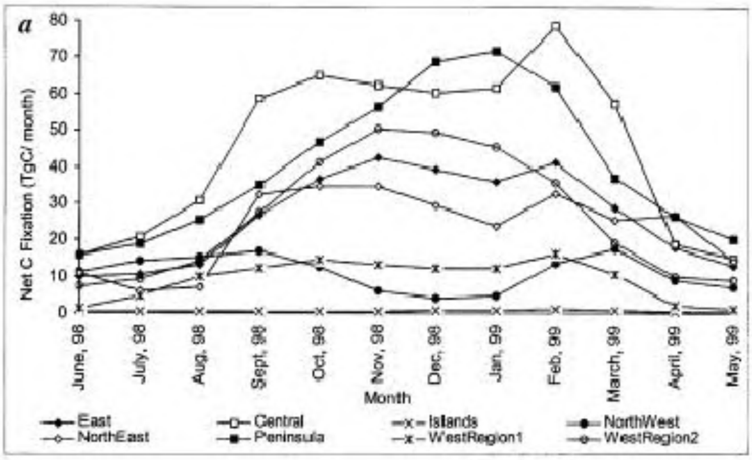

Figure 2 ***a*****.** Estimated Monthly Net Carbon Fixation (TgC) for different regions* of India (June 1998–May 1999). *Eight study regions with states/union territories in parentheses: East (Bihar, Orissa, Sikkim), Central (Uttar Pradesh, Madhya Pradesh), Islands (Andaman and Nicobar Islands, Lakshadweep), Northwest (Jammu and Kashmir, Himachal Pradesh, Haryana, Punjab, Chandigarh, Delhi), Northeast (Assam, Arunachal Pradesh, Manipur, Meghalaya, Mizoram, Nagaland, Tripura), Peninsular (Andhra Pradesh, Karnataka, Goa, Kerala, Tamil Nadu, Pondicherry), Western Region 1 (Rajasthan), and Western Region 2 (Gujarat, Maharashtra, Daman and Diu, Dadra Nagar Haveli).

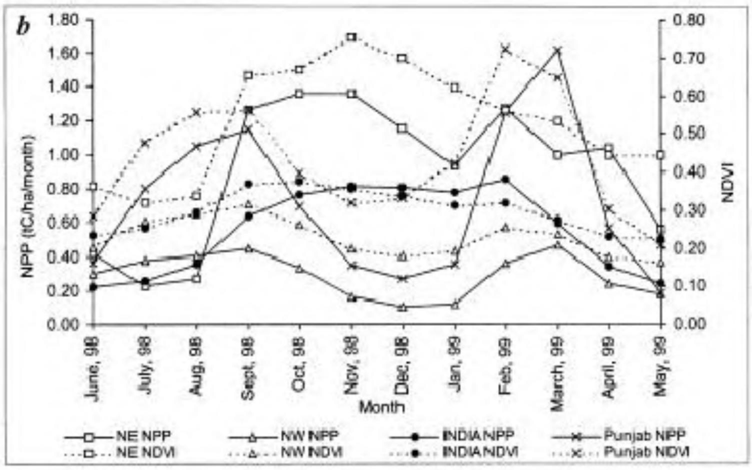

Figure 2 ***b*****.** Estimated monthly variations in NPP and NDVI for North East and North West regions, Punjab state and India (June 1998–May 1999). NE, North East region; NW, North West region.

mates[12], signifying relative dominance of the agro ecosystem and depleted biomass status in India.

While these results quantify atmosphere to biosphere carbon flux for 1998–99 season, there may be some inherent uncertainties in these estimates. The uncertainties arise from (a) model inputs[7] mainly the constant photosynthetic efficiency of 1.10 over all land cover types although it is highly determined by vegetation type, stage, and water stress, and (b) daily solar radiation and temperature, as Indian data may be under-represented in the global dataset. This RS-based analysis estimated higher NPP as compared to the earlier ecological studies-based Indian estimates. Study could highlight strong monthly variations in NPP across different regions of India with high net carbon fixation in winter as compared to monsoon season. Studies on field measured NPP and carbon flux through eddy correlation are needed urgently in order to validate these estimates and for arriving at improved understanding of terrestrial Net Primary Productivity over India.

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Equity in climate change treaty

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The Kyoto Protocol of the United Nations Framework Convention on Climate Change seeks to achieve climate stability and sustainable development through global cooperation. Even with spectacular advances in climate science, projected economic and health benefits of greenhouse gas mitigation, and presence of all the key elements for an effective treaty in the Kyoto Protocol, climate change negotiations remain inconclusive. Arguably, this is so because a widespread concern on equity is yet to be resolved. Here I reexamine the equity in climate change treaty. Political leadership, scientific community and civil society in several nations have maintained that the democratic norms for climate governance are a prerequisite for crafting a successful climate change treaty. Principle of equal per capita emission entitlements is now emerging as the key option beyond current impasse. Although not required under the Kyoto Protocol, several developing nations are taking responsible action to mitigate climate change. Principle of equal per capita emission entitlements is a just solution to successfully implement climate treaty aimed at climate change mitigation, adaptation and sustainable development. Without a full and unequivocal commitment to equity and democratic governance by a cohesive humanity, any international climate change treaty will have only limited utility.

REGIONAL and global variability in the earth's climate has been part of the natural phenomenon throughout the Holocene[1–5] and earlier[6–8], shaping interactions of life with the biosphere and adaptations to global change[9–11]. However, recent anthropogenic warming of climate system[12,13] and its projected impacts are clearly discernible from the accumulating recent evidence[14]. The United Nations Framework Convention on Climate change, 1992 (UNFCCC)[15] and its Kyoto Protocol, 1997, therefore, are crucial instruments for the global life-support system by stabilizing concentration of the greenhouse gases (GHGs), particularly carbon dioxide (CO_2) in the atmosphere. The most effective way to reduce CO_2 emissions with the economic growth and equity is to bring radical changes in the technology of energy production, distribution, storage and conversion[16]. Direct reduction of GHGs emanating from the current use of fossil fuel is urgently warranted, even as the tree plantations and multifunctional forests provide some respite and new research efforts explore cleaner sources of energy (for example, gas hydrates/hydrogen from biomass[17]).

The limits of global warming potentials are an important tool for policy decisions[18]. Stabilization of GHG concentration at a level that prevents dangerous anthropogenic interference with the climate system has been spelt out as the long-term objective in Article 2 of UNFCCC. Atmospheric CO_2 stabilization target as low as 450 ppm may be required to prevent coral-reef bleaching, shutdown of thermohaline circulation and sea-level rise due to disintegration of the West Antarctic Ice Sheet[19]. Furthermore, delay in responsible actions until 2020 may foreclose the option of stabilizing CO_2 concentrations at 450 ppm, particularly if the terrestrial carbon sinks become variable; and 'delaying reductions by industrial countries beyond 2010 risks foreclosing the 450 ppm option'[19] (Table 1).

A considerable part of the global land area was progressively affected by a significant change in extreme climatic events during the second half of the 20th Century[20]. Further, modelling studies suggest that about 25% of the protected areas globally will witness ecosystem transformation in the next century, even if the costs of emission reduction reach 2% of per capita consumption[21]. Mitigation projects may avoid many of these impacts, but stabilization at 550 ppm appears to be critical to avoid or reduce most of the projected impacts in the unmitigated scenario[22]. Even a mitigation cost of 5% of global income per year by the end of this century may be acceptable, as mitigation may result in tenfold increase in global income[23]. Urgent and bold steps are thus required to address the climate change.

At a time when the Eighth Conference of the Parties (CoP 8) to the UNFCCC in New Delhi has concluded, and CoP 9 is over, it is pertinent to examine critical science and policy that may be crucial for a forward step toward implementation of an effective climate policy.

Here, I address the equity in climate change treaty. The analysis builds beyond arguments initiated by Agarwal and Narain[24], Paul *et al.*[25], Daniel[26] and Baer *et al.*[27],

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Table 1. Atmospheric CO_2 concentration and dangerous anthropogenic interferences to the climate system

Target for atmospheric CO_2 stabilization (ppm)	Corresponding warming over the next 100 years (°C)	Effect on coral-reef	Effect on West Antarctic Ice Sheet (WAIS) and Greenland Ice Sheet	Effect on thermohaline circulation (THC)
450	1.2–2.3	Full protection of coral reef not possible	Disintegration may be averted	Shutdown of THC is avoided
550	1.5–2.9	Full protection of coral reef not possible	Slow disintegration	Disintegration of THC is feared
650	1.7–3.2	Extinction of reef	Fast disintegration	Shutdown of THC is feared

among others, by taking stock of fresh insights that have become available since.

The Kyoto process

In response to the climate crisis, more than 160 nations adopted the UNFCCC in 1992. It acknowledged the scientific basis of climate change. Its long-term objective is to prevent anthropogenic interference with the climate system, and division of roles and responsibilities between industrialized and developing countries. The UNFCCC also set the goal of stabilizing GHG emissions at 1990 levels by the year 2000. The initial failure of the Framework Convention to reduce emissions led nations to develop the Kyoto Protocol in 1997, in order to force GHG emission reductions in a cost-effective manner.

The Kyoto Protocol establishes the Clean Development Mechanism (CDM) to mitigate the climate change and promote sustainable development. Article 12.2 states: 'The purpose of the clean development mechanism shall be to assist Parties not included in Annexe I in achieving sustainable development and in contributing to the ultimate objective of the Convention, and to assist Parties included in Annexe I in achieving compliance with their quantified emission limitation and reduction commitments under Article 3.'

Under Article 3.1 of the Kyoto Protocol, the Annexe I parties have agreed to limit and reduce their emissions of greenhouse gases between 2008 and 2012. They can take into account the afforestation and reforestation and other agreed land use, land-use change and forestry (LULUCF) options.

Even with spectacular advances in climate science, economic benefits of the Kyoto Protocol[28], numerous health benefits of greenhouse gas mitigation[29], and presence of all the key elements for an effective treaty on climate change in the Kyoto Protocol[30], the process of climate change negotiations remains inconclusive. This is so, I argue, because a widespread concern on equity has not yet been resolved. This has invited widespread criticism across disciplines. Barrett[31,32], in an economic analysis, suggests that the Kyoto Protocol is an example of how *not* to construct a treaty. Particularly, because negotiations commenced with short-term focus on agreement that the developed countries should reduce their GHG emissions by about 5% relative to 1990 by 2008–2012. Subsequently, they agreed that emission reductions should be realized cost-effectively under a 'flexible mechanism'. It was only presently that they got anxious about incentives for inclusive participation and full compliance. Barrett[31,32] contends that the process should have fared better had negotiators approached these issues conversely by assessments of possibility of a broad participation and achievement of full compliance, and modalities to reduce emissions in the long term. Further, tendency for differentiated responsibilities to 'encourage self-serving negotiation strategies'[33] has been particularly cited as reason for failure of the Kyoto process. This has resulted in belief among many people that the Kyoto Protocol is unlikely to succeed in mitigating the climate change.

Activities proposed to mitigate climate change through Joint Implementation (JI) and CDM have also been critiqued. The distinction drawn between the use of carbon sinks in developed countries under JI and their use in developing countries under the CDM is complex and 'they also clearly discriminate against developing nations'[34]. For example, developed countries can self-certify sequestration projects but projects in developing countries would be required to obtain prior approval from a subsidiary body, the CDM Executive Board, authorized to obtain detailed information. This is not the case with the Article 6-related Supervisory Committee on JI Projects[34]. These and several other mechanisms have potentially imposed additional costs of compliance on developing country projects. Such regulations 'virtually ignore the fundamental principle of sustainable economic growth and development embodied in the Convention and related international agreements'[34].

What are the economic reasons for the absence of worldwide GHG emission reductions? A recent study by Hackl and Pruckner[35] on efficient CO_2 abatement levels for 135 countries found that the Pareto-optimal solution would require CO_2 emissions to be reduced by 28% globally, while the Nash equilibrium would necessitate 21% emission reductions. Because only 7% of total emission reductions can be ascribed to the global public-goods effect, it cannot be assumed that climate change mitigation would occur by overcoming the free-rider behaviour. Rather, a deep concern for nature and society is called for: deeper beyond economic considerations, embedded in self-restraint, altruism and compassion.

Notwithstanding the divergence of opinions, can global community of nations, with a responsibility of not overlooking the linkages between climate change and sustainable development[36], afford a failed climate change treaty? If not, then, how can we move beyond the current deadlock? In order to assess these questions, we first need to examine the causes and spatial magnitude of GHG emissions.

Comfort vs survival emissions

Global carbon emissions average about 1 metric $tC\,yr^{-1}$ (ton per year) per person as against $5\,tC\,yr^{-1}$ being emitted in some affluent countries. Per capita emissions in the developing world are $\sim 0.6\,tC\,yr^{-1}$, and more than 50 developing countries have emissions under $0.2\,tC\,yr^{-1}$, mostly for subsistence[27]. Around the world, most people view extravagant CO_2 emissions as resulting largely from luxuries that are unavailable to people in developing nations, whereas they view the emissions of poor nations as primarily for basic human needs, such as food, energy, and shelter[37].

But environmental politics of large per capita emission in the developed world is often compared against an interesting issue that emerged only recently (but does not come under the purview of the Kyoto Protocol). A short time ago, we had witnessed valuable debate on the nature, dimensions and impact of brown haze on natural, social and economic systems[38–41]. Such debate is inevitable and healthy in science, particularly when scientific results have immediate political utility. Unfortunately, in case of the brown haze debate, there are at least three challenges: first, politics seems guiding the science rather than vice versa; second, available science itself may be inadequate to provide any clear guidance to climate policy; and third, methods applied to generate available knowledge on brown haze do not seem to have confirmed to high standards of methodological rigour set by IPCC (Intergovernmental Panel on Climate change)[42]. Arguably, current discussion may seem related to 'positions' and finding out justifications for those 'positions'. The purpose of scientific studies informing the policy process would be served further if the scientists help in characterizing the problem and generating policy options instead of defining the policy adoption. Such assessments, involving multidisciplinary research and review teams across several nations, are critically needed if they are to inform climate policy makers. Until then, brown haze will remain a lively issue of environmental politics, with positions taken and swords pulled out.

Whatever the case, in order to prevent levels of GHGs in the atmosphere from exceeding twice the preindustrial levels, average worldwide emissions must be capped at levels below $0.3\,tC\,yr^{-1}$ per capita for a future global population anticipated to reach 10 billion people. What are the motivations and policy for the developed and developing world to achieve such a target?

Human well-being and poverty eradication remain the priority of developing countries in order to achieve the ultimate goals of sustainable development. This entails integration of actions in key areas such as water, energy, health, agriculture and biodiversity, and to build on the outcomes of the World Summit on Sustainable Development. Moving in that direction requires a substantially increased share of renewable energy sources in order to cut emissions. The caveat, however, is that global energy policy must remain supportive to less-developed countries in their efforts to eradicate poverty. Thus, as the Delhi Ministerial Declaration on Climate change and Sustainable Development suggests, international cooperation must be promoted in development and dissemination of 'innovative technologies in respect of key sectors of development, particularly energy, and of investment in this regard, including through private sector involvement and market-oriented approaches, as well as supportive public policies'[43]. Realization of this vision is plausible only with the democratic climate governance.

Science and policy for democratic climate governance

Civil society, scientists and the Government of India (GOI) were among the pioneers in advancing the principle of equal per capita emission entitlement. GOI was the first to officially suggest the equal per capita entitlements approach at the CoP 1 of the UNFCCC in 1995. Since then, GOI continues to support the principle on grounds of equity and democratic governance that are reflected in statements such as 'equal per capita is an equitable norm and the per capita criterion is central to the determination of emission entitlements'[44–46].

Indeed, some of the leading scientists have argued for the long-term allocation of emissions based on equal rights to the atmospheric commons for every individual. Baer and colleagues[27] note: 'Adoption of the principle of equal per capita emissions rights could help resolve the objections of both developed and developing countries and ease the path for the community of nations to implement the Kyoto Protocol.' The concept has found acceptance throughout the developing world and elsewhere among governments, scientists, policy planners and environmental philosophers.

The often-cited objection to equal per capita principle has been that this will provide developing countries incentive for continued population growth. That is ill-founded because numerous studies in development discourse do not support this conjecture. Indeed, over the past three decades, with new technology, enhanced female literacy and education[47], and strengthened family-planning programmes, there have been spectacular increases in the use of contraception and corresponding declines in fertility and population growth rates[48]. Making such programmes more widely available to women in developing countries would further bring about a decline in birth rates[49]. Extension of voluntary family planning could make a large and cost-effective contribution to the reduction in GHGs. Indeed, the resources that may flow in through climate-mitigation projects under equitable regime shall help finance larger goals of poverty reduction including investment in health, education and ecosystem management. Such support is particularly important in the light of the fact that the effect of environmental pollution on women and children, and cascading effect of poverty–population–environmental degradation undermine the human well-being, particularly of women and children[42]. It also erodes their ability to cope and mitigate the consequence of changing environment.

Equal per capita emission entitlement brings equal responsibility to people and nations. A single international treaty is only one of the ways from which to move toward global management of GHGs. Bottom-up initiatives for carbon management by those individual nations which are not required to reduce emissions, provide an opportunity to learn from their efforts to move toward a more sustainable future[50]. Are there any signs of prudent behaviour in the developing world in terms of actions that contribute to climate change mitigation?

Mitigation of climate change by developing world

Independent studies suggest that developing countries are already making massive reductions to their GHG emissions. Although not required under the Kyoto Protocol, several developing countries, including India are already taking actions that have remarkable impact for global climate change mitigation. For example, a study published by Pew Center on Global Climate change, USA[37,51,52] notes that policies and schemes implemented by Brazil, China, India, Mexico, South Africa and Turkey have together reduced the growth of their GHG emissions by ~300 million tonnes per year over the past 30 years. The savings are the result of a wide range of programmes, from local renewable energy schemes to market reforms. For instance, in China alone, CO_2 emissions from fossil-fuel combustion declined from 2950 Tg (teragrams of CO_2, 1 Tg = 1 million tonnes) in 1996 to 2690 Tg in 2000, a reduction of 8.8% (i.e. about 1% of the global CO_2 emissions amounting to 25,300 Tg from fossil fuel combustion in 2000)[53].

We take India as an example. With a population of more than 1 billion people, India's per capita annual GDP is only $2358. However, India has stated commitment to reduce poverty by 2012 at a rate of 10% through full employment, food, energy, water, economic security and double per capita income. To achieve these goals, India has developed an open, market-based economy and a sophisticated science and technology programme. India's economy grew at a rate of almost 6.6% per year during the 1990s, nearly doubling over that time. Still, India's per capita electricity use averages only one-half that of China, and one-sixth of the world average[37].

India ratified the UNFCCC in 1993 and the Kyoto Protocol in 2002. Even as not required under the Kyoto Protocol, India is already implementing the climate change mitigation policies that have large impact on climate amelioration. Two sectors are particularly noteworthy: energy and forestry.

India's growth in energy-related CO_2 emissions was reduced over the last decade through economic restructuring, enforcement of existing environmental legislations, and programmes on renewable energy. As a result, in the year 2000 alone, energy policy initiatives reduced carbon emissions growth by 18 Mt, which is about 6% of India's gross energy-related carbon emissions[37].

Recent discovery of the largest natural gas reserve in the Krishna–Godavari basin, Andhra Pradesh, equivalent to ~1.2 billion barrels or 165 Mt of crude oil, is 40 times larger than Bombay High reserves and would further reduce energy-related carbon emission in India. The new-found reserve can meet the demand for gas in India over the next 100 years – a time span sufficient enough to allow scientists to search for other clean energy options.

The developing world is suggested to be responsible for most of the recent deforestation and forest fire induced CO_2 emissions. That may be true locally[54,55], but it is only part of the larger picture. Most of the human modification of the landscape over the past few centuries has occurred in the temperate latitudes converting forests and grasslands to highly productive croplands and pastures[56,57] emitting large amount of CO_2 in the atmosphere. Thus, if holistically compared to emissions due to current and historic land-use change and fossil-fuel emission in temperate latitudes, emission in the developing world is still small. Further, two recent studies that followed most robust methods available to determine the tropical forest cover, find that the situation in the tropics may not be as bad as has often been projected in official documents.

Determination of deforestation rates of the world's humid tropical forests by Achard *et al.*[58], employing the global imaging capabilities of earth-observing satellite remote sensing imagery, with better global consistency and with greater accuracy than previously available, concluded that global net rate of change in forest cover during the period 1990–1997 for the humid tropics is 23% lower than the generally accepted rate provided by the Food and Agriculture Organization. Achard *et al.* further noted that actual annual net flux using this study leads to a global estimate of 0.64 ± 0.21 GtC yr^{-1} for the period from 1990 to 1997. This is far lower than the total annual net emission from land-use changes, primarily in the tropics (1.6 ± 0.8 GtC yr^{-1}) for the period from 1989 to 1998, as estimated by the IPCC[59].

The data in the study by Achard *et al.* pertain to humid tropical forest biome of Latin America, excluding Mexico and the Atlantic forests of Brazil; the humid tropical forest biome of Africa (Guineo-Congolian zone and Madagascar); and the humid tropical forest biome of Southeast Asia and India, including the dry biome of continental Southeast Asia. Compared to the humid tropics, net change in forest area is lower in the dry tropics and the average biomass of the tropical dry forests is less than half that of tropical humid forests. Taking this into account, a maximum estimate of global net emissions from land-use change in the world's tropical regions has been estimated to be 0.96 GtC yr^{-1} (ref. 58).

Another study by DeFries *et al.*[60] on carbon emissions from tropical deforestation and regrowth based on satellite observations for the 1980s and 1990s, notes that for the 1990s total tropical net change in forest area is 35% less than Forest Resource Assessment (FRA) remote-sensing survey and 53.6% less than FRA country data. Net carbon flux from tropical deforestation and regrowth in 1990s is 0.9 (0.5–1.4) Pg yr^{-1} (1 Pg C = 1 Gt C). Thus, both studies provide similar estimates of carbon flux from tropical deforestation (Table 2).

We turn again to India as an example where net rate of deforestation is negative. India is moving with policies and programmes to achieve the national forest policy goal of 33% forest/tree cover by having a total of 109 million hectare (M ha) area under the tree cover, out of the total 328 M ha geographical area of the country. Existing forest cover in India is currently 63.73 M ha and, in addition, 16 M ha of tree cover already exists outside forests. Thus, total land under forest/tree cover in India is currently 79.73 M ha. An additional 29.27 M ha area is to be brought under tree cover to achieve 33% green cover. Furthermore, about 31 M ha out of 63.73 M ha would need restoration to enhance the productivity of degraded forests and 29 M ha tree cover can be established through plantations on non-forestlands and agroecosystems. Thus, a total of 60 M ha land in India is proposed to be afforested/reforested in times ahead. These activities are expected to sequester additional carbon between 83.2 M tC and 202.67 M tC annually (Table 3; Figure 1). The potential quantum of carbon that may likely be sequestered is more than the total potential global market for carbon in the LULUCF sector in the first commitment period. These national initiatives are not only the responsible behaviour, they are also vital for climate change mitigation.

I do not wish to convey here that problems of tropical deforestation are either completely absent or need no attention. The emphasis is to put the reality in perspective. The estimates of reduced tropical deforestation notwithstanding, catastrophic events such as forest fires can release carbon in a particular year. The above analysis should not make developing countries complacent. Rather, the implication is that as tropical forests, soils and peatlands are large carbon pools, strengthening of the management regimes to save against wildfires is urgently required. Otherwise, emissions could be large. For example, the emissions from wildfires in Indonesia during the abnormally long El Niño dry season of 1997 were $0.81–2.57 \times 10^{15}$ g (Pg) or gigatonnes (Gt) – of carbon as a result of burning peat and vegetation[61]. This is equivalent to 13–40% of the mean annual global carbon emissions from fossil-fuel combustion. Although emission estimates due to fire seem to be unusually large, they are supported by independent studies[62] as well as collateral evaluative approaches[63] (Table 4). An effective fire-management regime is required to avoid recurrence of such events. Obviously, incentives for avoiding deforestation are required to be built within the Kyoto Protocol.

Table 2. Rate of carbon flux primarily from tropical deforestation

Data source and year of study	Year	Annual rate of carbon flux (Gt C yr^{-1})
IPCC (2000)[59]	1989–98	1.6 ± 0.8
Achard *et al.* (2002)[58]	1990–97	0.96
Defries *et al.* (2002)[60]	1990s	0.9 (0.5–1.4)

Table 3. Proposed afforestation and reforestation and potential carbon sequestration in India

		Rate of carbon gain (tC per ha/yr)		Total carbon sequestration (M tC/yr)	
Activity	Area (Mha)	IPCC Rates (ref. 59)	Rates based on average of two Indian studies (refs 98 and 99)	Based on IPCC rates	Based on the average rates of two Indian studies
Forest area to be restored to enhance productivity	31	1.75	5.20	54.25	161.20
Plantations under non-forest lands	29	1.00	1.43	29.00	41.47
Total	60			83.25	202.67

Table 4. Abrupt fire-induced carbon loss from Southeast Asian forests during El Niño

References and methodology used	Most likely carbon loss in GtC during the year noted within brackets*	Caveat/caution
Satellite imagery; ground measurement of peat depth; extrapolation of data (Page *et al.*[61])	0.81–2.57 (1997)	It is not a recurring phenomenon. Such an unusually high emission during the El Niño year, has neither been reported earlier nor subsequently
Inferences from atmospheric measurements of H_2/CO_2, CH_4/CO_2 and CO/CO_2 emission ratio related to forest fires (Langenfelds *et al.*[62])	0.6–3.5 (1994/1995) 0.8–3.7 (1997/1998)	Study does not exclude possible contribution from processes that are linked to climate forcing. Thus, fire could have been aggravated by El Niño and/or anthropogenic global climate-change itself. In addition, as the authors note, the large range in estimates is due to uncertainty in H_2/CO_2, CH_4/CO_2 emission ratios of fires in the years to which the studies pertain.
Inverse modelling using different subset of observations (Schimel and Baker[63])	1.1–1.5 (1997/1998)	Authors[63] note that this is a rough confirmation and the approach can provide only tentative conclusions

*By way of comparison, the ocean stored 14.8 Pg of anthropogenic carbon from mid-1980 to mid-1989 and 17.9 Pg of carbon from mid-1990 to mid-1999 (i.e. a net oceanic uptake of 1.6 and 2.0 ± 0.4 Pg C yr^{-1}, respectively)[100].

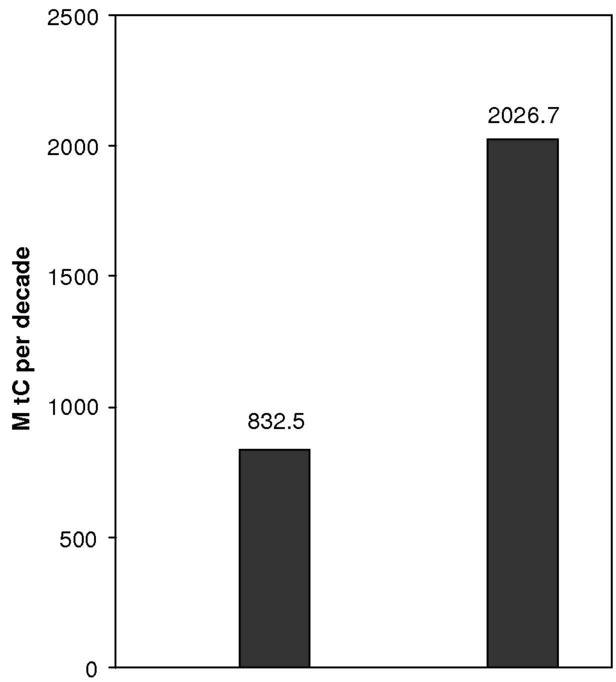

Figure 1. Range of potential carbon sequestration in Indian forests. If the restoration/plantation activities are carried out over 60 M ha as proposed in India, the decadal rate of additional carbon sequestration may be achieved between 832.5 M tC (based on IPCC rates of carbon sequestration) and 2026.70 M tC (taking rates from Indian field studies in tropical dry forests). Estimated district-level forest phytomass C densities in India range from 4.3 to 206.8 tC ha^{-1} (ref. 96). Other model simulations[97] suggest the sequestration potential of 6.937 G tC in aboveground vegetation of India in the next 50 years. A climate policy consistent with ecological, economic and social sustainability in developing countries will be crucial to establish synergy.

Biodiversity and the way ahead for synergy and sustainability

Even though science of climate change has progressed steadily, a lot more needs to be known to remove uncertainty. Particularly, climatic and environmental changes during the past 1000 years[64] can help us to know with absolute certainty if recent climate changes are anthropogenic and unprecedented. The first and the foremost task of global community of scientists, therefore, must be to generate enough science to persuade all nations to join the global society in implementing the climate change mitigation and adaptation. Nonetheless, it is prudent to note that even if in an unlikely event the entire science of climate change is proved wrong, Kyoto mechanisms still make a reasonable economic, social and ecological sense.

The policy implication for CDM that can help counter tropical deforestation and therefore global GHG emissions implies that a climate policy agreement will sooner or later have to be reached on how to account for the benefits of avoided deforestation[65], in addition to afforestation and reforestation, and incorporate them into climate change mitigation programmes[66,67]. Inclusions of avoided deforestation within the CDM, for example, can particularly help conserve biodiversity in the hotspots.

Biodiversity hotspots are ecosystems rich in endemic species, but threatened by anthropogenic activities. As many as 44% of all species of vascular plants and 35% of all species in four vertebrate groups are confined to 25 hotspots comprising only 1.4% of the land surface of the earth[68]. In 1995, more than 1.1 billion people, nearly 20% of the world population, were living within the broader definition of hotspots covering about 12% of the earth's terrestrial surface. Nearly 75 million people (i.e. 1.3% of the world population) were living within the three major tropical wilderness areas, representing an average density of about 8 people km^2. These areas are experiencing population growth at a rate of 3.1% yr^{-1}, which is more than twice the global rate[69]. Growth in household numbers globally and in countries with biodiversity hotspots, was more rapid than aggregate population growth between 1985 and 2000; adding 155 million more households in hotspot countries in 2000, and may likely add a projected 233 million additional households to hotspot countries during the period 2000–15 due to reduction in size of household (i.e. number of occupants in a house)[70]. Clearly, incentive structures for avoiding damage to natural ecosystems (such as avoided deforestation and hence avoiding GHG emissions and protection to biodiversity) due to increasing population and increasing households are required. Synergy in several fronts shall be required to achieve true sustainability as envisioned in the Kyoto Protocol.

The core development challenges are complex and manifold, but a synergy in policy and action is clearly plausible. In addition to climate change mitigation, there is a need to ensure productive work and a much better quality of life not only for the ~3 billion poor people today living on less than $2 per day but also for the 2–3 billion people that are likely to be added to the world's population over the next 30–50 years[71]. A further challenge is to save the young population from the environmental changes and consequent health hazards, because it may render populations unproductive, and therefore aggravate poverty. Saving children from the impact of climate change is most urgent because they are vulnerable in three ways[72]: (1) environmental changes due to anthropogenic GHGs can lead to respiratory diseases, sunburn, melanoma, and immunosuppression; (2) climate change may directly cause heat stroke, drowning, gastrointestinal diseases, and psychosocial maldevelopment; (3) ecologic alterations triggered by climate change can increase rates of malnutrition, allergies and exposure to mycotoxins, vector-borne diseases (malaria, dengue, encephalitides, Lyme disease), and emerging infectious diseases.

Further climate change is likely, given global industrial and political realities. With a changing climate and consequent sea-level rise and coastal flooding, disrupted monsoon and rainfall, and prolonged droughts, there could be as many as 200 million people as environmental refugees[73]. Science must help in the adaptation to climate change and eradication of poverty as well as environmental restoration through appropriate institutional mechanisms[74]. Global community has a shared responsibility to protect the environment, feed the hungry, heal the sick, provide dignity in work, and 'create space for the joy of self-expression'[75].

Climate change negotiators will also need to consistently remember the coherence among all the UN conventions having a bearing on the sustainability of the planet (Table 5). We need to comprehend potential synergies and identify opportunities for joint action under various agreements. Climate change mitigation and adaptation policies must be implemented with an overall approach to ecological, economic and social sustainability. Climate change mitigation actions that are in consonance with the Convention on Biological Diversity, Desertification Convention, and World Heritage Convention can bring human well-being and sustainability of various systems. What are the operational criteria to achieve such coherence?

In addition to recognition to the equal per capita emission entitlements as argued earlier, it would be useful to give priority to projects on climate change mitigation that meet a combined set of seven criteria, which can be verified through measurable indicators for ecological, economic and social sustainability: (i) reduction and/or sequestration of GHGs, (ii) biodiversity conservation and ecosystem functioning, (iii) yield of goods and services to local people, (iv) poverty reduction, (v) local empowerment and capacity development, (vi) synergy with objectives of international instrument and conventions, and (vii) coherence with local strategies for sustainable development.

Global society needs a new cultural paradigm embedded in unique human intelligence, equity of knowledge systems, and self-awareness in the face of crisis. Human security depends on equitable development rooted in fundamental principles of democracy, albeit within the means of nature. Sustainability with social justice can be achieved only through an unprecedented level of international cooperation rooted in a sense of compassion for both other peoples and other species[76]. As noted earlier, compassion, altruism and self-restraint are good virtues to interact within the human systems and between humans and other species[77]; however, compassion, must not be understood here as a feeling of pity towards developing nations; rather it might best be understood to 'have properly exercised towards *vulnerability* rather than *suffering*'[78] both in developed and developing countries, as well as application of democratic principles in the light of knowledge of responsibility and burden sharing for climate change. Shifting the emphasis from mere GHG emission reduction to sustainable development can contribute significantly to relieving the threat of human-induced climate change[79]. From a deep philosophical standpoint, the implementation of climate change mitigation policies must encompass social justice ingrained in equity and fairness.

Table 5. UN conventions with direct bearing on climate change mitigation policies

Instrument	Broad objective	Reference
Framework Convention on Climate change – The Kyoto Protocol	Climate change mitigation and sustainable development	http://unfccc.int/
Convention to Combat Desertification	Combating desertification that is expected to lead to sustainable development of countries affected by drought and desertification	http://www.unccd.int
Convention on Biological Diversity	To promote nature and human well-being	http://www.biodiv.org
World Heritage Convention	To protect and manage sites of exceptional importance to humanity	http://whc.unesco.org