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Ecology: Perspectives and Prospects for India

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ABSTRACT

The present article recounts historical perspectives and discuss recent developments in the field of ecology, global environmental challenges and the concept of sustainability. The key environmental issues and strategies and approaches for sustainable development are discussed with special reference to India.

Keywords: Ecology, Ecosystem. Planet boundaries, Sustainable development

INTRODUCTION

Population growth and energy uses are increasing and so is the environmental crisis. This has led to the emergence of the discipline of Environmental science. Environment implies the totality of conditions that influence the life of organisms. The survival and sustainability of life on this planet are now threatened. Evidently equitable resolution of the environmental issues is needed. Our urge to understand complex biological systems and their interaction with non-living elements is growing considerably. Barriers of disciplines are becoming porous to accommodate and address societal issues and concerns. In this context, being a cross-cutting, interdisciplinary science, ecology holds a key position.

While Ecology is the study of the structure and function of ‘nature’, environmental science deals with the application of scientific/technological tools for solving the environmental problems faced particularly by humans. The contemporary ecologists agree that ‘nature’ is heterogeneous, its patterns and dynamics are scale-dependent, and diversity and complexity are its inherent characters. Most of the front line global environmental problems, be it biodiversity loss or climate change, habitat fragmentation or population growth, soil degradation or pollution increase, etc., fall within the gambit of ecological studies and require a thorough understanding of ecological principles for resolution. The ecologists are frequently required to interpret the human-induced environmental changes and postulate varied scenarios for alternative policy options for legislative and implementable administrative decisions. Ecology has grown by internalizing the different disciplines of natural and, more recently, social sciences (Misra 1985), and with the passage of time, it is evolving as a science of Human Sustenance and Sustainability.

The present article aims to give an account of historical perspectives and discuss the recent developments in ecology, global environmental challenges and the concept of sustainability. The key environmental issues and strategies and approaches for sustainable development are discussed with special reference to India.

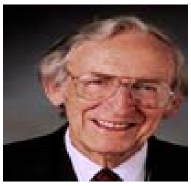
EVOLUTION OF ECOLOGICAL CONCEPTS

As philosophy or viewpoint, the roots of ecology lie in antiquity. All early humans depended on natural resources (mostly biological) largely to satisfy their hunger, and developed a basis for identification and assessing distribution of resources at a small scale. This was later replaced by innovative ways of utilization and assessment of resources on a large scale. Cultivation of plants and domestication of animals became a practice, and the knowledge base on nature and its components widened.

Initially, ecology started with descriptive accounts with a focus on biogeographical patterns and a strong

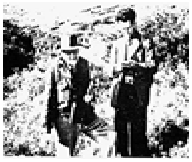
Box 1. Key players and landmarks in the development of Ecological thought

Ernest Haeckel (1869) The term Oekologie, as introduced by Haeckel, meant the study of the relationship of the animal to its organic as well as its inorganic environment.



E. P. Odum (1971) Defined Ecology as the totality of patterns of relations between organisms and their environment or study of structure and function of nature. He postulated that Nature is heterogeneous, its patterns and dynamics are scale-dependent and it is diverse and complexHis book *Fundamentals of Ecology* published in 1971 (first published in 1953) was instrumental in spreading ecological concepts.

R. Misra (1985) He defined Ecology as 'Science of Human Sustenance and Sustainability', internalising various disciplines including social sciences. Recall that C P Snow in 1959 (see Snow 2012) had lamented on the wide and detrimental divide between Science and Humanities and argued for making bridges between the two cultures for finding solutions to human problems.



J. Braun-Blanquet He followed the biogeographical and descriptive approach; and laid the foundation of phytosociology.

Frederick Clements He laid the foundations of the Dynamic Ecology approach, e.g. succession. His publication Plant succession: an analysis of the development of vegetation in 1916 was indeed a landmark in the development of ecology.

Charles Elton He formulated the concept of the food web, trophic pyramids (especially the pyramid of numbers) and niche. In 1927 he wrote the earliest textbook on animal ecology. His paper A trophic continuum derived from plant structure, animal size and a detritus cascade published in the Journal of Theoretical Biology in 1989 is a benchmark paper.

Arthur Tansley Formulated the concept of Ecosystem (1935) and defined it as the structural and functional entity of biotic communities and the environment.

Raymond Lindman He published a key paper in 1942 on the trophic dynamic aspect of ecology in *Ecology* 23 (4): 399-417 and established a theoretical model of nutrient cycling expressed explicitly in terms of energy flow and arriving at several very important relations regarding the flow of energy in ecosystems. This important paper was published posthumously.

R. H. Whittaker Laid the foundations of Quantitative Ecology; In 1970 wrote the famous textbook *Communities and Ecosystems*. His publication *Gradient Analysis of Vegetation* in *Biological Reviews*, 1967; forcefully advocated Gleasons' individualistic concept.

George M Van Dyne He laid the foundations of systems ecology in 1966 and headed the US IBP grassland biome study at Colorado State University. He published in 1966 *Ecosystems. Systems Ecology and Systems Ecologists* pronouncing and elaborating the concept of systems ecology.

taxonomic leaning. This biogeographical approach of ecology was strengthened by the contributions of early European (e.g. Braun-Blanquet 1932, Wulff 1943) and American ecologists (e. g. Cain 1944, Kuchler 1947). Landmarks and key global players in the development of ecological thoughts are included in Box 1.

In the Indian context, ecological literature began to accumulate in the form of floristic accounts following the establishment of the Botanical Survey of India (BSI) in 1889. The monumental book 'Silviculture of Indian Trees' by Troup (1921) included a basic understanding of the biology and regeneration of trees in relation to environmental conditions. H. G. Champion used the available climatic and forest floristic data to propose the first-ever classification of Forests of India and Burma in 1936. G. S. Puri published two volumes of Indian Forest Ecology in 1960 (Oxford Book Co. Delhi). Ecologists continue to study species, their characteristics and their assemblages in relation to environment. For example, in a study by Chaturvedi et al. (2021), "gradient of soil moisture indicated a continuum of drought adapting strategies in tropical dry forest trees and that "the stem water potential significantly influenced drought avoiding species assemblage, while wood specific gravity and canopy cover significantly influenced drought tolerant tree assemblage. Functional traits explained up to 60% variance in biomass accumulation capacity of trees, and the drought tolerant trees registered highest biomass and biomass accumulation capacity." Chaturvedi et al. (2021) further reported that "the tree species experiencing drought conditions, maintained their physiological functions by three strategies, i.e., drought avoidance, drought resistance, and drought tolerance and that "the drought avoiding species tend to avoid drought period by shedding their leaves at the start of dry period, while drought tolerant as well as drought resistant species had ability to tolerate water stress to greater extent, and they are able to sustain foliage for longer period. The tree species appear to be arranged on a continuum between the two strategies of resource exploitation (viz., acquisitive and conservative strategies), which also explains the continuous variation in functional traits in a gradient of soil moisture stress." Nevertheless, we still have limited information about the dynamic interactions between environmental factors and tree physiological attributes modulating species distribution in tropical dry forest ecosystems."

The mathematical and statistical approaches in ecology with strong experimental background emerged by the second half of the 20th century. This was the take-off stage of quantitative ecology. The studies made by Goodall (1963), Gounot (1969), Whittaker (1970), etc., strengthened this approach. The beginning of the 20th century also saw the emergence of experimental and dynamic ecology (e.g., Clements 1916). "Karl Friederich in 1927 proposed the concept of *holocoenotic environment* which states that it is impossible to isolate the importance of single environmental factors because the factors are interdependent and synergistic" (see Billings 1964). The concept of 'ecosystem' (a structural and functional entity of biotic communities and their environment) was introduced by Tansley (1935). Charles Elton (1927), an English ecologist, had already developed the concept of ecological niches, and the pyramid of numbers.

Lindeman (1942) elaborated the "trophic-dynamic" aspect of ecology, with emphasis on energy flow and food chains. E.P. Odum's *Fundamentals of Ecology*, first published in 1953, provided a solid framework for ecosystem theory and revolutionized education as well as research in ecology. Energy flow, mineral-nutrient cycling, population biology and ecosystem dynamics became the central themes in ecology.

During the 1950s, there was widespread concern about rapidly burgeoning resource-related and environmental problems facing mankind. This led to the development of the International Biological Programme (IBP) in the 1960s by International Council of Scientific Unions (ICSU), which had a dramatic effect on the study, practice and scope of ecology. The goal of IBP was to explore "The Biological Basis of Productivity and Human Welfare". This programme made substantial progress in advancing the understanding of ecosystems, particularly the operating processes: productivity, water and mineral-nutrient cycling, competition, predation, decomposition and the role of detritus in the ecosystems. The programme revolutionized research and teaching worldwide. The IBP helped in promoting the ecosystem concept (see Coleman 2010 for details); with the emphasis on production at primary, secondary and tertiary levels in terrestrial and aquatic ecosystems.

The IBP also generated interest in establishing Long-term Ecology Experiments on several sites, (later called long-term ecological research, LTER). In fact, “of the first six long-term ecological research sites (LTER sites) established in 1980, four originated from previous IBP projects” (Coleman 2010). “Long-term studies are designed to capture the effects of the environment and biotic interactions (including human impact) in on-going ecological processes. LTERs are also required to validate mechanistic and predictive models of global change and ecological results” (Hobbie 2003). “These sites now form an international network (ILTER). Presently there are 44 member networks grouped into four major regions, Americas, East-Asia-Pacific, Africa and Europe.”

In 1971, UNESCO launched an interdisciplinary programme of research, the Man and the Biosphere Programme (MAB), “which emphasizes an ecological approach to the study of interrelationships between man and the environment. It is meant to focus on the general study of the structure and functioning of the biosphere and its ecological divisions, the changes brought about by man in the biosphere and its resources, and on the overall effects of these changes upon the human species itself.” Thus man and nature interactions became a central theme in ecology. Ecology began to be recognized as a problem-solving science. One of the major outcomes of the MAB programme was the establishment of Biosphere Reserves across the world. The IUCN Commission on Ecosystem Management has adopted an ecosystem approach for implementing action-oriented programmes for biodiversity conservation, sustainable human livelihoods, empowerment of local people and maintaining ecosystem productivity.

During the last two decades, the major global environmental changes that are being realized and are occurring at an ever-increasing pace, have been the focus of research under the Millennium Ecosystems Assessment programme, launched in June 2001 by the UN. The MEA recognized the ecosystem services and their relationship with human wellbeing (Fig. 1)

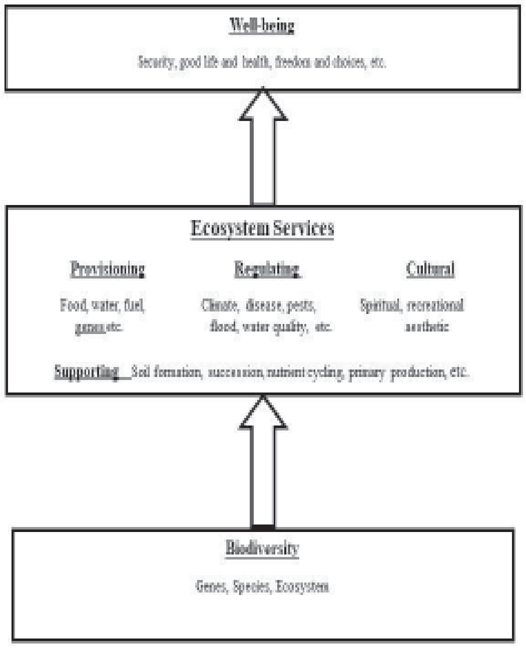


Figure 1. Relationship of ecosystem services with human well being and biodiversity (based on MEA, 2005)

ICSU launched an International Geosphere-Biosphere Programme (IGBP) in 1987 which has been one of the world’s leading scientific research programmes studying changes to the global environment. The overall goal of IGBP was to describe and understand the interactive physical, chemical and biological processes that regulate the total Earth system, the unique environment that it provides for life, the changes that are occurring in this system, and the manner in which they are influenced by human activities.

A new platform for international scientific collaboration, *Future Earth was announced in June 2012 at the UN Conference on Sustainable Development (Rio+20) and became operational at the end of 2015.* Future Earth has a focus on research for global sustainability in view of the risks posed by global environmental change. This platform builds on more than three decades of global environmental change research through the World Climate Research Programme, the International Geosphere-Biosphere Programme (IGBP), DIVERSITAS and the International Human Dimensions Programme on Global Environmental Change (IHDP).

With regard to the progress of ecology in India, the years 1936-37 proved a milestone. “These years marked the return to India of late F. R. Bharucha and R. Misra, after their postgraduate studies abroad. Misra laid the foundation of both field and experimental ecology in India, and in the process established the oldest, actively continuing centre of ecological research at the Banaras Hindu University. Simultaneously, while working at the Royal Institute of Science, Bombay, Bharucha introduced the methodology of Zurich-Montpellier School of vegetation analysis in India.” Besides Universities, a variety of national and state-level, problem- or region-oriented Institutes have come up, generating

Box 2. A synoptic view of contributions of Indian ecologists

University/Institution and leading ecologists with their major research contributions

Department of Botany, Banaras Hindu University, Varanasi (The mid-1950s onwards)
R. Misra, K.C. Misra, J.S. Singh, K.P. Singh; others were D.N. Rao, R.S. Ambasht, A.S. Raghubanshi, R. Sagar, H. Singh, N. Ghosal, Jitendra Pandey

One of the early leading groups in production ecology in the world, the time of which coincided with IBP; fine root production in trees, the functioning of tropical dry forests particularly nutrient cycling, the role of nutrient immobilization by litter microbes in dry tropical forests, diversity patters; restoration of mine spoils, autecology, the ecology of invasive alien species, air and water pollution. *The Ecological Workbook* by R. Misra played a key role in expanding ecology in India.

French Institute, Pondicherry (Latter half of the 20th century)
V.M. Meher-Homji, P. Legris, F, Blasco, P. Pascal,

Extensive vegetation cartography and bioclimate mapping; ecological nature of Shola grasslands, classification of the vegetation of Western Ghats.

Sagar University, Sagar (1960s)
S.C. Pandeya, L.P. Mall, G.P. Mishra

A full paper on ecology was developed for the first time in India by R. Misra in 1955-56 on Forests and grasslands of Central India

North-Eastern Hill University, Shillong (the 1970s onwards)
P.S. Ramakrishnan, R.S. Tripathi, H.N. Pandey, S.K. Barik

Ecology of various aspects of shifting cultivation, population ecology, invasive alien species, and species regeneration, tree phenology, traditional knowledge system.

Kashmir University, Srinagar (the 1960s onwards)
V. Kaul, D.P. Zutshi, Zafar Reshi

Lake limnology, lake classification on the basis of thermal stratification, macrophytic and plankton communities. Invasive alien species is the current research area.

CAZRI, Jodhpur and IGFRI, Jhansi (the 1970s onwards)
K.A.Shankarnaryan, P.M. Dabadghao, P.S. Pathak, V. Shankar, C.B. Pandey

Grazing land ecology, agroforestry. The book, *Grass Cover of India*, by K.A. Shankarnarayan, and P.M. Dabadghao.

Kumaun University, Nainital (1977 onwards)
J.S. Singh (1977-1985), S.P. Singh (Until 2005)

Vegetation analysis; structure and functioning of forest ecosystems along an extraordinarily wide altitudinal range; characterization of oak and pine forest ecosystems, the linkage between forest and agriculture; phenology, diversity, and regeneration of trees; resorption of nutrients from senescing leaves; tree water relations; mycorrhizal ecology.

Contd.....

Box 2. contd...

incorporation of Himalayan forest ecosystem services in national accounting. The research of the centre resulted in a major book on Himalayan forests and the establishment of GovindBallabh Pant Institute of Himalayan Environment and Development.

Vikram University, Ujjain (Early 1960-1970)
L.P. Mall
Grassland vegetation, mangrove vegetation, and other stressed plants.

Kurukshetra University, Kurukshetra (the 1970s onwards)
J.S. Singh, P.S. Yadava, S.R.Gupta
Productivity, Soil respiration, litter decomposition, and carbon dynamics in early successional grasslands; ecological rehabilitation of salt-affected soils, forest ecosystems of Siwaliks.

School of Environmental Sciences, JNU, New Delhi (the 1980s onwards)
P.S. Ramakrishnan, C.K.Varshney, Brij Gopal, K.G. Saxena, P. K. Joshi, S. Garkoti
Indigenous ecological knowledge systems, air pollution, Environmental flows, ecosystem services.

Delhi University, Delhi (the 1990s onwards)
C. R. Babu, Inderjit Singh, M. K. Pandit, K.S. Rao
Ecological restoration using legumes microbes, and soil invertebrates; invasive alien species; biodiversity, Himalayan Ecology and Conservation.

University of Rajasthan, Jaipur (the 1980s and 1990s)
Brij Gopal
Macrophytic vegetation productivity and decomposition.

Centre for Ecological Sciences (CES), Indian institute of Science (IISC) Bengaluru (1973 onwards)
Madhav Gadgil, Raghvendra Gadakar, R. Sukumar
Promoting human dimensions in ecology; Social biology of **Ropalidia**; the research was converted into a major book; Human-elephant conflict; dynamics of tropical forests.

Indian Institute of Remote Sensing (IIRS), Dehradun (the 1990s onwards)
P.S.Roy, S.P.S. Kushwaha.
Development of geospatial database on the vegetation of large areas using satellite data with a focus on physiognomy, species composition, biodiversity, fragmentation.

University of Agricultural Sciences, Bengaluru (the 1990s onwards)
K.N. Ganeshaiah, R.Uma Shankaar
Biodiversity database.

ATREE (Ashoka Trust for Research in Ecology and Environment, Bengaluru) (the 1990s onwards)
K.S. Bawa and several others
NTFPs (Non-Timber Forest Products), vegetation, climate change, invasive alien species.

Wildlife Institute of India, Dehradun (the 1990s onwards)
H.S. Pawar, R. Chellam, A.J.T. John Singh, G.S. Rawat
Wildlife-focused areas and high altitude vegetation.

Pondicherry University, Pondicherry (the 1990s onwards)
S.B. Chaphekar, N. Parthasarathy
Tropical forests of Eastern Ghats-biodiversity, species composition, Lianas.

a mass of data on India's environment and bioresources. Notable players and centres of ecological research in India are recalled in Box 2, (for more details see Singh 2014).

"In spite of a clear understanding of the close link of humans with natural ecosystems and their capacity to alter/modify the properties of the ecosystem, they were considered external to the ecosystems" (Callicott et al. 1999). However, "with the advent of landscape ecology in the 1970s and the realization of the fact that human activities have environmental effects over large areas than local ecosystems" (Forman & Gordon 1986), the human dimensions started to be a central theme of ecological studies.

HUMAN DIMENSIONS AND CONCEPT OF SUSTAINABILITY

Articulation of human dimensions in ecology shifted the emphasis towards predator controlled or consumer-controlled ecosystems in contrast to the concept of a producer-controlled ecosystem. Disturbances are being seen as a driving force in the evolution of ecological systems. More researches are being focused on human-impacted ecosystems (e.g., Ramakrishnan 1992). Recent studies that contribute to improving the quality of life have created a definite niche. This includes sustainability, equity and species coexistence and components of our heritage in a biologically and culturally diverse world (Huntley et al. 1991). The applied fields like restoration ecology, landscape ecology and ecotoxicology are receiving increasing attention. The process-level understanding of decomposition, nutrient cycling and regulation of ecosystem functions through top-down and bottom-up controls are being put to practice to improve productivity, profitability and more importantly, the sustainability of wide-ranging terrestrial and aquatic systems. These considerations usually advocate two basic concepts- sustainable yield and sustainable development. "The genesis of these concepts can be traced to the conservation philosophies, which dominated the first three-quarters of the 20thcentury i.e. (1) resource conservation (resourcism- natural is valued only to the extent that it is humanly useful) and (ii) wilderness (preservationism)" (Salwasser 1990, Callicott et al. 1999).

The concept of sustained yield is largely based on the harvestable surplus that so much and no more can be received continuously. The concept of sustainable yield attracted considerable opposition from conservation biologists particularly in view of the fact that most species are not harvestable resources. "And many of the species face the danger of genetic impoverishment, local extirpation, and global extinction not due to over-harvesting but because their habitats are being polluted and destroyed" (Ehrlich 1988).

SUSTAINABLE DEVELOPMENT AND ECOLOGICAL SUSTAINABILITY

As defined in the Brundtland Report (WCED 1987), sustainable development is "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (Box 3). This was further strengthened at the United Nations Conference on Environment and Development held at Rio de Janeiro in 1992 and the World Summit on Sustainable Development held at Johannesburg in 2002. Sustainable development is more commonly understood to mean economic development that does not appreciably harm the natural environment. Another sustain-rooted conservation concept- ecological sustainability focuses on conserving the biota of ecosystems that are inhabited by humans and are economically exploited, in simple words, ecological sustainability is meeting human needs without compromising the ecosystem health (Callicott and Mumford 1997).

Box 3. Brundtland and her report

Gro Harlem Brundtland, Prime minister of Norway who headed the World Commission on Environment and Development. The report of the commission is titled Our Common Future which for the first time defined sustainable development in 1987.

The ecological interpretation of sustainability and the emerging conservation concept- ecosystem health, have both anthropocentric and ecocentric value dimensions (Callicott and Mumford 1997).

"Such realizations have called upon two separate disciplines (i.e. ecologists and social scientists who have traditionally worked separately) to integrate their approaches in a complementary manner" (Huntley et al. 1991) "to address the issues of physical, biological and socio-economic components of ecosystems." Ultimately, this must address the question of most fundamental importance that of the earth's human population supporting capacity.

ECOSYSTEM HEALTH AND BIOLOGICAL INTEGRITY

A healthy ecosystem is able to provide a flow of essential services to the society without which human civilization would cease to thrive. Unfortunately, these undervalued services are being impaired and destroyed. "The Living Planet Index (a measure of the natural wealth of Earth's ecosystems) declined by about 33% between 1970 and 1999, and the Ecological Footprint (the area required to produce food, materials and energy) increased by 50% between 1970 and 1997, and has far exceeded the existing biological capacity in most Asian countries" (Wu and Overton 2002). It is clear that the ecological footprint or demand has far exceeded the biocapacity of our planet so that now equivalent to 1.5 Earths are needed to meet the current demands of humanity on nature (Fig 2).

According to Global Footprint Network 2014 ,during the past 50 years, while the earth's biocapacity has increased from 9.9 to 12 billion gha, the world population has increased from 3.1 to 6.9 billion, and thus, per capita ecological footprint has increased from 2.5 to 2.6 gha (Fig.3). Evidently, the available planetary resources are under huge stress and are thus deteriorating. The main causes of disruption are land degradation and biodiversity loss: Over 40% of the vegetal land surface of the Earth has been directly disturbed (Daily 1995) and "its natural production capacity has been reduced, diverted or destroyed" (Vitousek et al. 1986). Current extinction rates caused by human activities are orders of magnitude higher than natural background levels (Pimm et al. 1995, see Singh 2001).

DEFORESTATION AND FRAGMENTATION

"Forests covered about 50% of the earth's land area 8000 years ago, as opposed to 30% today" (Ball 2001). "Tropical regions lost 15 2 million hectares of forests per year during the 1990s and forest degradation was most extensive in Southeast Asia (0 42% per year)" (UNFAO 2001). "Forest fragmentation replaces large areas of native forest with other ecosystems leaving isolated forest patches, with deleterious consequences for most of the native forest biota" (Murcia. 1995). With an increasing

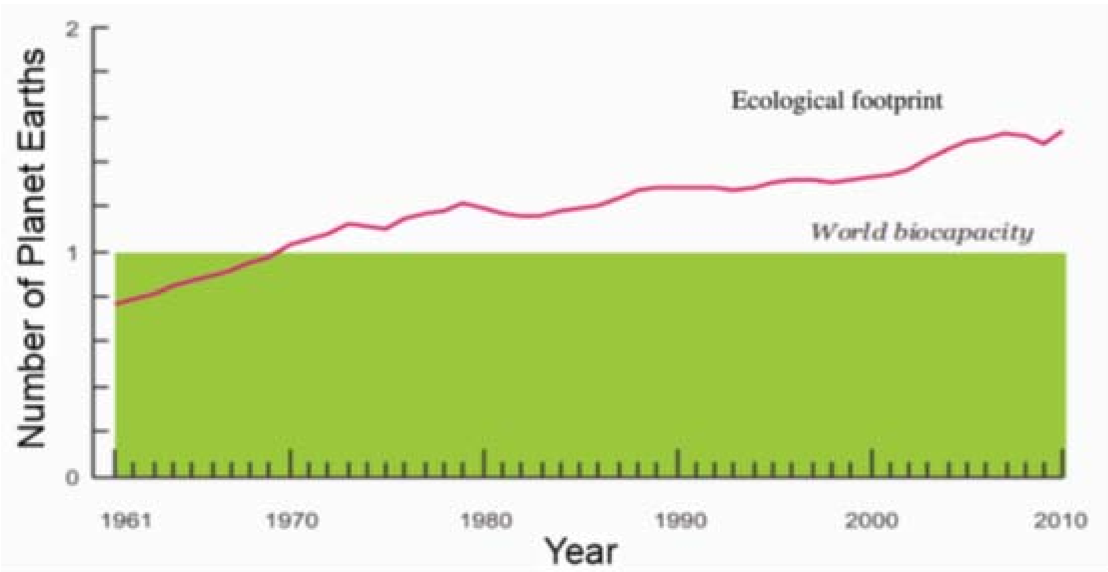


Figure 2**.** Ecological footprint vis-à-vis world biocapacity (after Global Footprint, 2014).

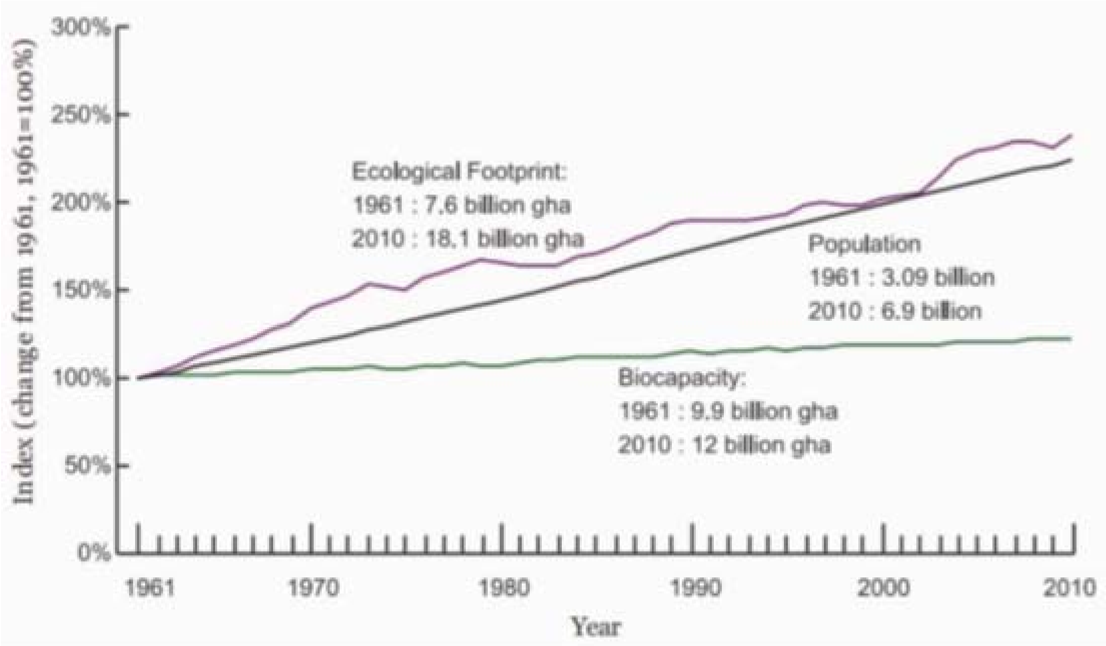


Figure 3. Trends in earth's biocapacity, ecological footprint and world population (after Global Footprint Network, 2014)

number of habitats becoming fragmented, we are faced with the task of conserving a patchy world. There are two seemingly contrasting options "preserve optimal habitat quality wherever it can be found' as opposed to "preserve a large number of well-connected patches" (Roslin 2002).

INTENSIFICATION OF AGRICULTURE

'Land conversion from natural ecosystems to simplified agroecosystems results in a substantial reduction in biodiversity and a decrease in habitat for displaced wildlife and plant communities' (Cassman et al. 2003). Historically, humans have increased agricultural output mainly by bringing more land into production (Lambin et al. 2003). However, the increase in the world's food production over the last decades was mostly due to agricultural intensification which is defined as 'higher levels of inputs and the increased output of cultivated or reared products per unit area and time' (Tilman 1999). Contemporary literature indicates that world grain harvested area per person has been consistently declining, global use of N and P fertilizers, global use of pesticides and the number of pesticide-resistant species have been consistently increasing. The global irrigation water use and world S and N emissions from fossil fuel have also increased tremendously. Atmospheric nitrogen (N) deposition is a matter of serious concern for the structure and functioning of global ecosystems, but the effect of N application on species diversity (D), primary productivity (P), and stability (S) of tropical ecosystems is relatively unknown. Verma and Sagar (2019) report that 'the N applied to these ecosystems caused significant variations in species composition, diversity, productivity and stability'". Verma and Sagar (2019) further report that 'relationships between diversity and stability differed under different N doses. "Dissimilatory nitrate reduction to ammonium (DNRA) in soils is a newly appreciated pathway of nitrogen (N) cycling in terrestrial ecosystems; it occurs in the same environmental conditions where denitrification does. It converts NO3- to NH4+, hence conserves nitrate from leaching and gaseous losses and enriches soils with readily available NH4+-N to primary producers and heterotrophic microorganisms. Therefore, DNRA may be treated as a tool to make ground-water pollution free, soils healthy and environment cleaner" (see Pandey et al. 2020).

"Water used for irrigation accounts for 80% of all freshwater" (Rosegrant et al. 2002). "Nitrogen (N) fertilizer applied to agricultural land comprises more than 50% of the global reactive N load attributable to human activities" (Smil 1999). High input

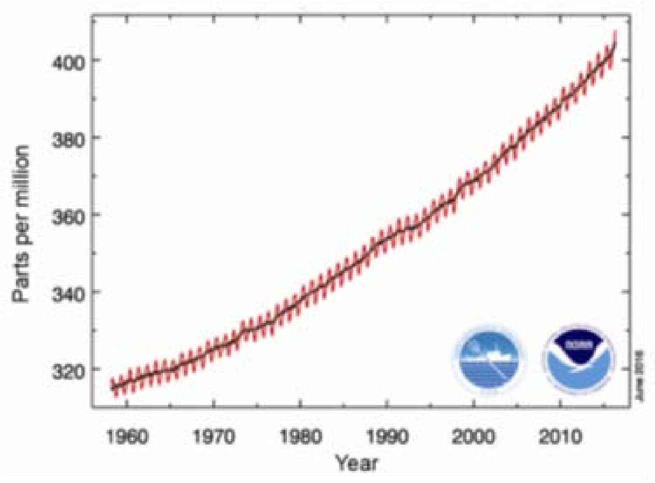


Figure 4. The trend of CO_2 measured at Mauna Loa Laboratory, Hawaii, USA accessed from http://www.esrl.noaa.gov/gmd/ccgg/trends/full.html, on 28 Feburary 2021).

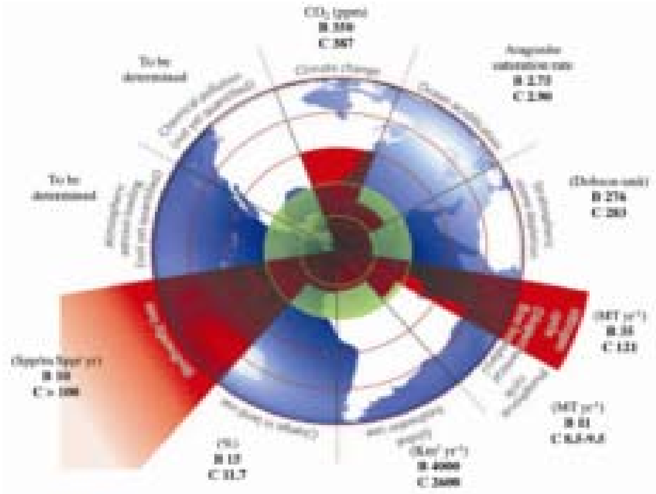


Figure 5. The nine planetary boundaries as safe operating space for humanity (based on Rockström *et al.*) B, Proposed boundary; C, Current status (after Singh 2020).

agriculture has many negative environmental consequences (Dobson et al. 1997, Matson et al. 1997, Vitousek et al. 1997a).

ENVIRONMENTAL POLLUTION

Heavy use of coal, high-sulphur fuels and N fertilizers and growth in vehicular traffic has increased the atmospheric pollution load (Fig. 4). The rising levels of total suspended particles, respirable particles and nanoparticles are posing a huge risk to human health. The contamination of air, water and soil is leading to the accelerating accumulation of toxic metals in the human food chain.

"*Planetary boundaries* is the central concept in an Earth system framework proposed by a group of Earth system and environmental scientists led by Johan Rockström from the Stockholm Resilience Centre and Will Steffen from the Australian National University". In 2009, the group proposed a framework of "planetary boundaries" designed to define a "safe operating space for humanity" for the international community, including governments at all levels, international organizations, civil society, the scientific community and the private sector", as a "precondition for sustainable development" (Rockström et al. 2009). This framework is based on" scientific research that indicates that since the Industrial Revolution, human actions have gradually become the main driver of global environmental change." The scientists assert that "once the human activity has passed certain thresholds or tipping points, defined as "planetary boundaries", there is a risk of "irreversible and abrupt environmental change" (Fig.5). "The updated analysis and quantification shows that four of the nine planetary boundaries have now been crossed as a result of human activity" (Steffen et al. 2015).

BIOLOGICAL INVASIONS

The frequency of biological invasions has increased. "Presently the alien invasive species constitute a global challenge of great magnitude by posing a great threat to biological diversity, harming human health and causing enormous economic losses" (G1SP 2001; http://www.diversitasinternational.org/resources/publications/news letters-1). The concept of biological integrity is receiving increasing attention because biodiversity may be artificially increased by introducing exotic species into vacant or under-exploited habitats, thereby disturbing the integrity of a biotic community. Disturbance in biological integrity can result in competitive exclusion of sensitive and endemic species (Cailicott et al. 1999). Interestingly, plant invasions are most pervasive in areas of high plant endemism posing a still greater threat to native biodiversity (Stockwell et al. 2003). Biodiversity and its changes driven by invasive alien plants (IAPs) are inextricably linked with human health (Rai and Singh, 2020). These health impacts can be both in positive (e.g., use of plant parts in ethno-medicine and mosquito repellent extracted from *Lantana camara*) and negative sense (direct effects or as vector of human diseases). In this sense, *L. camara* acts as favourable habitat for tse-tse fly (*Glossina* spp.) which causes sleeping sickness and *Parthenium hysterophorus* serves as a vector of malaria. Another IAP *Ixodes scapularis* acts as vector of *Borrelia burgdorferi*, responsible for Lyme disease in humans. Direct health effects of IAPs such as *Ambrosia artemisiifolia* (common ragweed) and *P. hysterophorus* are observed in the form of induced allergic responses in the human population. In addition to terrestrial IAPs, several aquatic plant invaders such as *Phragmites australis*, *Eichhornia crassipes*, *Arundo donax* and *Typha* sp. also act as reservoir of vector-borne pathogens like West Nile virus (Rai and Singh 2020). In view of several direct and indirect adverse effects of IAPs, the National Invasive Species Council (NISC) was set up to study the health risks associated with biotic invasions. Likewise, Lancet Commission on Planetary Health also included this subject of IAPs-human health interactions (see Rai and Singh 2020).

GLOBAL WARMING AND ECOLOGICAL CONSIDERATIONS

Among the most obvious consequences of global warming is the change in the altitudinal and latitudinal distribution of organisms and their assemblages. While affecting the distribution, phenology and physiology of the organisms at the individual level (IPCC 2001), these shifts merit consideration with regard to changes in both structural and functional properties of the ecosystems. In the Indian context, Himalayan mountains are supposed to be the most sensitive to these effects. Rapid glacial melt can cause serious flood damage in heavily populated regions, and as the glaciers recede, large regional populations that rely on the glacial run-off for water supply could experience severe water shortage. For example, in northern India, a large population depends on the tributaries of the glacier-fed Indus and Ganga rivers for irrigation and drinking water. But as the glaciers melt, these rivers are expected to swell initially followed by very low levels of water in subsequent years. “Data from 49 monitoring stations across Nepal indicate that air temperatures in the area are substantially higher than they were in the 1970s and as a result, some glaciers are retreating by 30-100 m a year in Nepal and Bhutan, creating unstable lakes” (McDowell 2002). “From a much wider perspective, the expected rise in sea level will have profound effects on human sustenance and sustainability of coastal habitats around the world including India” (IPCC 2001).

INITIATIVES FOR ENVIRONMENTAL SECURITY AND SUSTAINABLE DEVELOPMENT IN INDIA: PROGRESS AND GAPS THEREIN

In spite of strong traditions of nature preservation and its due recognition in the Indian Constitution (Article 48 a) “the State shall endeavour to protect and improve the environment and to safeguard forests and wildlife in the country” the real orientation towards contemporary environmental issues began in the aftermath of the 1972 Stockholm Conference on Human Environment. In this conference, the then Prime Minister of India, Mrs Indira Gandhi forcefully emphasized that the removal of poverty should form an integral part of an environmental strategy for the world. Since then, integration of poverty alleviation with environmental protection became a reality in India. Between the Stockholm Conference and the World Summit on Sustainable Development, India has established a fairly strong organizational structure and legal and policy framework for the protection of the environment, focusing on poverty alleviation and natural resource conservation.

Setting up of a Department of Environment in 1980 and its further up-gradation as a full-fledged Ministry of Environment and Forests (MoEF) in 1985 strengthened the country’s progress in this direction. The Environment (Protection) Act 1986, was an ‘umbrella legislation’, which empowered the central government to take appropriate measures for the purpose of protecting and improving the environment. Subsequently, a number of legislations, policies and programmes were initiated.to promote protection, conservation and sustainable use of the country's natural resources, although their implementation has remained a problem. Indian judiciary has played a laudable role through pro-environment judgments. The National Conservation Strategy and Policy Statement on Environment and Development, 1992 outlined the specific means through which environmental considerations could become a significant part of the developmental process. India is a signatory to the Convention on Biological Diversity (CBD), and initiated the countrywide process of developing a National Biodiversity Strategy and Action Plan (NBSAP). A Biological Diversity Act, 2002, has been notified to provide for the conservation of biodiversity, sustainable use of its components and equitable sharing of its benefits.

The biodiversity documentation centre in Bangalore is developing a comprehensive database on biological resources and their distribution which could be useful for formulating location specific conservation strategies, developing the biodiversity atlases as well as sustainable management of plant resources (Ganeshaiah et al. 2002). Similar efforts to develop biodiversity atlases of Northeast India, Western Ghats, Western Himalaya and Andaman Nicobar islands have been made (Anon. 2002a, 2002b, 2002c).

India acceded to the Montreal Protocol along with its London Amendment in June 1992. The MoEF has established an Ozone Cell and the Steering Committee on the Montreal Protocol to facilitate the implementation of the programme. Also, the Government of India ratified Framework Convention on Climate Change (FCCC). MoEF, the nodal agency in the country, has constituted Working Groups on the FCCC and Kyoto Protocols and a Task Group on the pilot phase of activity implemented jointly to look at specific issues under the Climate Change Convention

In spite of these and other initiatives, India still needs to make considerable strides (Singh 1991a). The burgeoning mass of data gathered through research has largely remained untranslated into management practices. For India, a formidable issue is the available land/water mass (2.5% of the world) for a rapidly increasing population (16% of the world). This creates enormous pressure on natural resources and human development as reflected by poverty and inequality, quality of water resources and environmental health risks (MoEF 2002a, 2002b). As per UND, India ranks 131 among 189 countries in terms of human development index data for 2020.

With only 23.33% of forest area (including nearly 42% as degraded forests), we still are far behind the national goal of 33% of the total area under forests set by the National Forest Policy, 1988. The rapid deterioration of land resources is yet another major concern. Due to the increasing demand for land by the ever-growing population, nearly 5.0% of the country's land is degraded at varying levels. The problems associated with water scarcity (both qualitative and quantitative) are aggravating with every passing day. India is among 17 countries that are mostly water scarce, and in 2025 will not have enough water to maintain 1990 levels of per capita food production from irrigated agriculture and meat industry, household and environmental needs (Seckler et al. 1999).

Environmental health risks arise due to poverty, unsafe drinking water, sanitation in rural and urban areas, air quality, indoor air pollution, unsafe solid waste management, and agro-industrial pollution. The quality of air in most of urban India has deteriorated to an alarming level. The faulty disposal of municipal, hazardous and medical wastes cause many types of diseases. Chemical contamination of harvestable portions of crops and vegetables, particularly by heavy metals, from sources such as industries, vehicles, pesticides contaminated irrigation water are matters of growing concern. Likewise, the rapid developmental activities and increasing population density are putting the coastal zones of India under severe stress. The wetland systems are now among the threatened categories. Similar is the case of the Indian Mountains where the pressures on natural systems are increasing at an alarming rate.

India needs to evolve a suitable strategy and implementable action plan wherein the issues of environmental protection and sustainable development are addressed in an integrated, holistic manner. The strategy has to be multi-sectoral and interdisciplinary and incorporate possibilities of linking local specificity with global generalization. The strong compartmentalization of disciplines, sub-disciplines, and specializations have hampered communication across the compartment boundaries. While this compartmentalization is inevitable, understanding interfaces of disciplines or sub-disciplines may have great value.

VISION FOR MITIGATING THE PROBLEMS

The interface of Ecology - Economics

To some extent, understanding both issues is embedded in the emerging concept of ecological economics (FE). EE integrates the study and management of nature and economies so that the cost of damage done to the air, water, soil and biota, and that of restoring this damage can be articulated in redefining development goals and in recalculating gross national product. However, the functioning of interdependent ecological- economics system is complex wherein the transformation of energy and materials between human economies and their natural ecosystems are subject to the laws of thermodynamics, The simple assumptions of conventional economics about nature as an unlimited source and sink lacked ecological perspectives and ignored the deeper implications. The concept of EE, in a way, focuses on issues of economic and ecological sustainability. But the sustainable management of both systems is tricky, especially in the present scenario when incentives to maximize short - term economic growth or gain are strong. Further, the unified approach of integrating ecology and economics also raises the question of time scale in the development process and the preservation of the ecosystem. The ecosystems operate on a geological time scale, whereas the economic processes in terms of sustainability are viewed on a human time scale. These realizations call for a convergence of options and approaches of both the disciplines and need thorough study.

We need to consider issues of equilibrating mechanisms between human society and nature. Our emphasis should be on maintaining ecosystem health and harnessing the services they provide.

Focusing on Ecosystem Health and Ecosystem Services from both economic as well as an ecological point of view, maintenance of eco-system health emerges as the most important issue to be addressed. Considering the diversity of ecosystems and their sensitivity to human or climate-induced perturbations we need to develop capabilities to maintain the integrity of these ecosystems. In this context following points deserve priority.

A thorough investigation of native and endemic biotic components of the ecosystems must attract the highest attention. This information is desired not only to address environmental issues such as conservation priorities (species/communities/ ecosystems) but also the emerging international economic scenario.

Monitoring the changes in ecosystems, including those due to the invasion of alien species, is yet another aspect that needs immediate attention. Changes in natural patterns and processes across disturbance gradients would provide a means for predicting the future structure and dynamics of ecosystems.

Ecosystem health has a direct bearing on the well-being of human societies. Unfortunately, the services rendered by natural ecosystems are being impaired and destroyed by a wide variety of human activities.

Maintaining ecological integrity involves protecting total native biodiversity at all levels, as well as the ecological patterns and processes that maintain that diversity. ‘Anticipate and prevent’ instead of ‘react and cure’ strategy must be firmly established for dealing with environmental pollution. The use of plants and natural / constructed ecosystems in pollution abatement needs to be thoroughly studied and applied.

The eroding ecosystem health and integrity calls for concerted restoration efforts. “Ecological restoration is the process of renewing and maintaining ecosystems that have been degraded damaged or destroyed” (SER 2002).

Besides focusing on hardcore long-term, large-scale research and development initiatives, there is a need for extensive information generation and its wide dissemination across the country.

Urban Green Infrastructure

We need to place more emphasis on urban green infrastructure. Urban green infrastructure (UGI) can be defined as "the network of planned and unplanned green spaces, spanning both the public and private realms, and managed as an integrated system to provide a range of benefits" (Norton et al. 2015); in fact, it can be visualized as an interconnected network of green spaces that conserves natural ecosystem values and functions and provides associated benefits to human populations (Benedict and McMahon, 2002). "The green infrastructure of urban areas provides all the four kinds of ecosystem services (provisioning, regulating, supporting and cultural) recognized by the Millennium Ecosystem Assessment, encompassing multifunctional benefits such as social, economic, cultural and environmental, in an integrated and interconnected manner" (Singh et al. 2020). The components of green infrastructure contribute to the stabilization and regulation of weather conditions and preservation of the ecosystem services in the urban areas. Green infrastructure helps in pollution mitigation, carbon sequestration, temperature moderation, climate change mitigation and storm) water management. It also provides a habitat for organisms. "Being novel ecosystems, they provide a diversity of habitat for plants and animals such as lawns, wastelands, herbaceous borders, shrubberies and hedges, parklands, gardens, street trees and pavement cracks and walls" (see Singh et al., 2018 for details)

Sensitizing the Youth

The coordinated countrywide effort of the Indian Academy of Sciences to deploy student power for monitoring India's life cape diversity (Gadgi11996) is an initiative wherein the involvement of young students in environmental education is focused. Likewise, the ongoing programmes for promoting outreach through conservation education in the Himalayan region (Dhar et al. 2002) have shown the tremendous potential of involving school children in problem-solving areas of ecology and environment in the country.

Based on the outcomes of MEA, ICSU-UNESCO-UNU (2008) (ICSU-UNESCO-UNU https://www.yumpu.com/en/document/view/52113635/icsu-unesco-unu-ecosystem-report (2008)) identified key knowledge gaps and prioritized research needs that should be filled through additional scientific research at global and regional scales. Regional research activities may focus on understanding the full dynamics of the relationships among drivers, ecosystems and human well-being and understanding the trade-offs among ecosystem services across spatial and temporal scales to generate information directly relevant to decision-makers.

Integrative Ecology

Holling (1998) identified "two cultures in ecology", an "analytic approach that develops its activity by expanding the existing knowledge base through experiments", and an "integrative approach where progress is achieved through the integration of existing knowledge, from different disciplines." To address concerns of integration, we have to adopt a research approach that comprises: (1) the inclusion of diverse taxa of animals, plants, and microbes; (2) the integration of individual, population, community, and ecosystem levels of the organization; (3) the incorporation of more than one patch type in a heterogeneous landscape; and (4) a combination of long-term monitoring and manipulative field experiments. Integrative ecology needs long-term data on ecosystem properties for which a meaningful ecosystem monitoring programme has to be put in place. "Long-term studies need to be designed to capture the effects of the environment and biotic interactions (including human impact) in on-going ecological processes" (Pickett 1991). "Long-term ecological research sites (LTERs) are also required to validate mechanistic and predictive models of global change and ecological results" (Pickett 1991).

Ecological Informatics & Databases

The exponentially increasing volume of primary data in the digital form generated by automated data collection through long-term observations, experiments, simulations, sensors and satellites need to be archived and preserved so that they are available and appropriate for contemporary discovery and future re-use. In India, NRSA, NCL, ATREE and UAS are active in this direction (Jeeva Sampada and IBIN are good starts in this direction), but data generated by universities and research institutions are yet to be standardized and archived in openly accessible databases so that concept reviewers, modelling community and decision-makers can use them meaningfully. Lack of common methodology, absence of cross laboratory calibrations and different frequency and units of measurements make most of the Indian ecology and environment research data hard to use and interpret. We need national standard methodologies for ecological and environmental parameters; this is one aspect which MoEF and other central organisations should take on an urgent basis.

Ecosystem Modelling

Enhancing predictive capacity is one of the most important endeavours for Indian ecologists. We need to develop and use models to formulate testable hypotheses, forecast change, inform research priorities, and integrate information from monitoring systems, observation networks, and experiments. “Mechanistic, quantitative simulation modelling, should be a core component of long-term ecological research” (McNaughton and Campbell 1991). “These models need to address the system-level linkages between drivers, feedbacks, ecosystem services, economic valuation and human well-being indicators.”

HUMAN DIMENSIONS AND SUSTAINABILITY SCIENCE

There is still a major divide between social sciences and natural sciences. Ecology can bridge this gap. “There is a need to initiate coordinated research to understand the dynamics of the relationship between humans and ecosystems” (ICSU-UNESCO-UNU 2008). Such an initiative should enhance understanding of: (a) the nature of interactions among drivers; (b) the relative influence of ecosystem change on human well-being; (c) interactions among ecosystem services; (d) cross-scale (temporal and spatial) interactions of drivers, services, and responses; (e) how ecosystem services and human well-being outcomes can be modified by changes in policies or management; and (f) how to model the relationship between humans and ecosystems at local, regional and global scales. Therefore, our new ecological research priorities should include (a) promotion of research that integrates global and local perspectives in a place-based framework for understanding the interactions between environment and society; (b) focus on a limited set of understudied questions, those that underpin the understanding of those interactions; and (c) promotion of more efficient use of existing tools and processes that link knowledge and action.

STRENGTHENING COMMUNICATIONS

Despite producing an enormous amount of new information, ecologists are often unable to convey knowledge effectively to the public and to policy-makers. Unless the discoveries of ecological science are rapidly translated into meaningful actions (i.e.Translational Ecology), they will remain quietly archived while the biosphere degrades. Therefore, we have to communicate results and uncertainties in formats useful and accessible to policy makers and resource managers. “Public outreach should be recognized as an appropriate and important professional endeavor”. This is so important that Pace et al. (2010) have suggested that “such efforts towards communicating science to the common public and policymakers should be considered in merit evaluations”.

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