# Shaping science as the prime mover of sustainable agriculture for food and nutrition security in an era of environmental degradation and climate change

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**At the time of India's independence in 1947, India's food production for national food security was highly insufficient. Malthusian scourge in the backdrop of Bengal famine of 1943 was looming. It was at a time of critical food shortage in the 1960s, commodity-centric exploitative agriculture, miscalled as Green Revolution, was ushered in by Swaminathan–Borlaug partnership. It changed India's image then as begging bowl to bread basket! As had been foreseen and forewarned, the Green Revolution resulted in environmental degradation, enhanced social inequities and had little to do with sustainable agriculture and rural development. With the lessons learnt, Swaminathan developed a systems approach-based evergreen revolution to achieve productivity in perpetuity without accompanying environmental and social harm. It is also designed to fight both the famines of food and rural livelihoods with the help of ecotechnologies having pro-nature, pro-poor, pro-women and pro-livelihood orientation. The present article elaborates these aspects.**

**Keywords:** Climate change, food and nutrition security, science for sustainable agriculture.

## Technology versus ecology and future food security

IT may seem strange, but is true that curiosity and the ingenuity of the modern human species, the *Homo sapiens*, have brought the humanity, the biosphere and the planet Earth at the cross-roads. All the other living organisms endowed with far less ingenuity have been living in perfect harmony with nature, and have not caused such massive degradation of the planetary resources and impairment of the ecosystems services. And the anthropogenic dimension in the climate change referred to as 'Anthropocene', supplementing the 'Holocene', the warming inter-glacial period of about 10,000 years[1], is no longer questionable. In fact, global warming-induced climate change is fast approaching the 'tipping point', which is a threat to the very survival of human species and possibly several others.

At some point of time in the organic evolution, brain development in the precursor species of the genus *Homo* gained preponderance over all other physical parameters for wider adaptation. Jane Goodall's[2] extensive studies on chimpanzees suggest that curiosity and adventure of ideas as well as ability for innovations had pre-existed the origin of modern human species. Until about 10–12 millennia, the modern human species (*H. sapiens*) which had already been in existence for about 200 to 250 thousand years, spent much of its time in gathering food from the wild flora and hunting animals. These activities left little time for fulfillment of its innate curiosity and manifestation of its ingenuity. For reasons beyond comprehension, the *H. sapiens* (sapiens = wise), made the transition from foraging to farming just about 10,000 years ago. The farming included cultivation of edible crops and domestication of wild animals which are referred to as the farm animals for draught, milk and meat. Wild dogs were domesticated as pet animals/partners in hunting much earlier, about 38,000 years ago, when *H. sapiens* were still foragers. The transition from foraging to farming was an irreversible change in a forward direction, called the 'ratchet' by Ruth De Fries[3]. The term 'ratchet' is quite appropriate considering the statement of late B. P. Pal. In his foreword to the book '*A History of Agriculture in India*' Pal[4] wrote: 'The history of agriculture is inextricably interwoven with the progress of civilization because it was the taking up of agriculture that made it possible for primitive man to live in selected spots, forming a society, and growing a significant portion of his food nearby. This enabled human beings to find a certain amount of leisure to create initial ingredients of what is known as civilization.' Thus, it is the farming that started about 10,000 years or so, that enabled the human species to find expression for its curiosity and ingenuity. Curiosity of the humans is the driving force for systematized observation of the physical world, and this led to a branch of knowledge called 'science'. The human species went further from being merely

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satisfied with observations of the natural world to making endeavours to mimic and even elucidate the structures and functions of both the inanimate and animate worlds. That denoted the beginning of an era of experimentation, a direct outcome of the ingenuity of the modern human species.

During the past 5–6 millennia, human curiosity and ingenuity to understand everything from the nature of solar system, the origin of the universe, the structure and function of all living beings from microbes to man, have been mutually reinforcing, in the sense that one acting as a catalyst for the other. Thus, ingenuity led to the birth of an era of 'industrial revolution' in 1780, with the invention of steam engine by James Watt. Soon, the technologically powerful Western countries colonized the 'biodiversity-rich', but 'technology-poor' countries located largely within 22° to the south and north of the equator. Fixing low cost for the raw materials and much highly value-added cost to the finished products divided the technology-rich, and technology-poor nations into 'rich' and 'poor' respectively. Today, these are the 'developed' and 'developing nations' respectively. On hindsight, it seems unfortunate that the developing countries are now following the same path of development that the western nations had taken. As Gandhiji once remarked, several 'Earths' would be needed to attain the status of 'developed' nations, if every developing nation in the world would want to become 'developed' in only a materialistic sense. The notion of 'developed' and 'developing' nations purely in terms of GDP and economic growth is basically flawed, as it ignores ecological and social dimensions. Criteria for 'being developed' ought to be based on people's good health, altruism, peace and happiness and above all ability to live in harmony with nature like all the other animals do. The energy intensive development path is clearly unsustainable and impacts are already felt, e.g. rapid increases in desertification in China and collapsing oceanic biodiversity[5]. A deep concern from the point of emission of greenhouse gases (GHGs) is that the technology-driven economic growth has been substantially fossil fuel energy-dependent. Further, accelerated economic growth rests on a fallacy that the natural resources are infinite. The former has led to climate change whereas the latter is now accelerating the inter-generational inequity for resources necessary for their own development of the future generations.

In the last five decades starting with the U.N. Conference on Human Environment held in June 1972, in Stockholm, there has been a growing realization that poverty and environmental degradation (that broadly includes biodiversity loss, depletion of resources necessary for development and agricultural productivity, impairment of the ecosystems services and climate change) are closely interlinked in a mutually reinforcing manner. Needless to say, Carson[6] and Swaminathan[7] had initiated discussions concerning the environmental and social impacts of the then new technologies. In his famous address in 1968, even before the release of the 'Wheat Revolution Stamp' to commemorate the dramatic increase in wheat productivity by the Government of India, Swaminathan[7] had forewarned against the environmental and social harm that an 'exploitative agriculture' (later misnamed as the 'Green Revolution' by William Gaud of US Agency for International Development) would cause in the long-run. The exploitative agriculture involved monocropping over large contiguous areas with dwarf and semi-dwarf wheat varieties having genetic potential for yield increase in response to inputs of chemical fertilizers and copious irrigation. Unfortunately his warnings were not heeded and hence the Green Revolution has degenerated into Greed Revolution. Schweitzer[8] had gone further to declare, 'Man has lost the capacity to foresee and forestall, he will end by destroying the earth'. In the past four decades, the world has witnessed several UN Conferences such as the UN Conference on Environment and Development in June 1992 in Rio de Janeiro, Brazil; World Summit on Sustainable Development in 2002 in Johannesburg, South Africa and RIO+20 on Sustainable Development in June 2012 in Rio de Janeiro. Yet, the progress towards sustainable development has been far below expectation. And the climate change has emerged as a great risk to agriculture, whether exploitative or sustainable. The jeopardy of collapse now addresses not just the civilization but the very continuation of life itself. Misuse of science and technology geared towards transforming low entropic raw natural resources into high entropic (i.e. value-added consumer goods) largely for economic gains, has brought the planet on the brink of disaster. In the social realm, inequalities have led to a situation where 20% of the richest own 80% of the wealth and resources of the planet while about 1.0 billion people out of 7.2 billion people in the world do not have even the most basic need of food and nutrition security as well as sanitation. An ethical question posed in this context is whether science and technology have brought wealth and prosperity just to a few nations and people, but extreme poverty, deprivation and hunger to a large number of nations and people. Is it that recent developments in science and technology are being deliberately designed to make the rich richer, the poor to sink into abject poverty and hunger? The answer is in the affirmative. Technology development including the genetically engineered crops have been 'top-down' in mode. The crops and traits for genetic engineering are chosen by the multinational companies. Thus, the herbicide-tolerant (Ht) and insect borer pest-resistant *Bt* (*Bacillus thuringiensis*) transgenic crops have been inundating the market. Many geneticists and evolutionary biologists are quite aware that pests would develop 'genetic shield' (i.e. resistance) against such pesticides. In the USA, extensive use of Ht transgenic corn and soybean has exerted 'selection pressure' on a number of weed species to develop genetic resistance against the weedicide (in this case 'Roundup' with glyphosate as the main ingredient). The resultant 'super weeds' are causing havoc in over 400–500 thousand hectares of farmland across a dozen states. That glyphosate and the adjuvants which constitute the 'Roundup' are known endocrine-disrupters and possibly carcinogens is yet another cause of concern[9,10].

In order to gain a little longer existence of life on Planet Earth, the technology development needs to be based on the principles of ecological integrity, sustainable human welfare and ensuring social as well as gender equalities. The economic dimension of the technologies, besides the goal of profit, must be to widen the resource base for increasing rural livelihoods. Swaminathan[11–16] has, therefore, proposed concepts and paradigms such as 'techniracy', biovillage and modern ICT-based Village Knowledge Centres (VKCs), etc. in order to harness ecotechnologies for sustainable rural livelihoods and food security at the individual household level. Ecotechnologies are the resultant of blending frontier technologies (e.g. space, nuclear, bio-, nano and such technologies) with traditional knowledge and ecological prudence of the indigenous rural women and men. Consequently, the ecotechnologies acquire pro-nature, pro-poor, pro-women and pro-livelihood orientation unlike the frontier technologies in their raw science-based form. Most simply stated, ecotechnologies are the technologies with social and ecological principles or dimensions. Surely, with such advances in basic sciences in various disciplines, very powerful technologies to bring about dramatic increases in agricultural productivity will keep on emerging, but the need of the hour is to assess their suitability to maintain the integrity of the ecological foundations, social and gender equities, etc. The point is that 'technological push' must have equally powerful 'ecological and social pull'.

## Evolution of scientific approach to farming

### *Inorganic chemical fertilizers and chemical pesticides*

Experience with farming over several millennia has been compiled in 'Roman Farm Management: the treatises of Cato and Varro[17], and among its valuable lessons, the one that defines agriculture as a science is: 'agriculture is a science which teaches us what crops should be planted in each kind of soil, and what operations are to be carried out, in order that the land may produce the highest yields in perpetuity'. Agriculture, the science of farm production, is surely the 'Mother of all Sciences'.

The human population of the world during the First BCE was less than 10 million. The world population reached about 500 million in the year 1650, and it rose to about 950 million in 1798 when Thomas Robert Malthus noted that geometric population growth would inevitably outstrip food production, leaving society destitute and hungry. His 'Essay on the Principle of Population' has been long regarded as 'Malthusian curse' than a rational analysis to be deeply concerned about. It led to neglect of family planning! Malthus considered that population of 950 million people of his time was already quite huge and it could hardly be supported by the 'limited resources' of Earth. About 100 years later, in 1900, the global human population reached about 1.6 billion. The population doubling rate was about 0.7–0.8% per year. By 1965, the global population totalled at 3.3 billion. The population growth rate was about 2% per year, representing a doubling time of 36 years. In 2000, the population of the world reached 6.0 billion. Within the next 11 years the global population had grown to touch the 7.0 billion mark. The various projections suggest that global human population might stabilize at about 9.0 billion in 2050. So, Malthus was right about geometric progression in human population growth. But the argument has been that humanity has not perished in hunger and starvation! In particular, India with about 18% of the global human population plus 15% of the global livestock with only 2.3% of geographical areas, 4.2% of freshwater sources, 1% of forest area and 0.5% of pasture/gracing areas is still able to produce adequate food for all its people, albeit the inequality in food security at the individual household level. In this context, Jeffrey Sachs of Health Institute in his foreword to the book '*From Green to Evergreen Revolution*'[18] wrote: 'few people in modern history have done more to help humanity surmount the Malthusian challenge than M. S. Swaminathan'. Swaminathan[7] had, of course, set aside exploitative agriculture as the pathway to surmount Malthusian scourge over long-periods of time. He had, instead designed and operationalized evergreen revolution discussed in this paper.

The development of environment-degrading technological breakthroughs dates back to the late 18th century with the beginning of an era of industrial revolution. For farm operations such as ploughing, drawing water for irrigation, etc. the draught power of farm animals was gradually replaced with fossil fuel-powered tractors, pumps, harvesters, mills, etc. The Haber–Bosch chemical process fixed the atmospheric nitrogen in the form of ammonium nitrate which the plants could utilize from the soil for luxuriant growth and higher productivity. But, it involves the use of high levels of energy derived from burning of the fossil fuels. Before the chemical synthesis of ammonia commercially was known, the fixation of nitrate in the soil was almost entirely through 'biological nitrogen fixation' by a class of nitrogen-fixing microbes. In a few countries, night soil was applied to the soil to enrich nitrogen content of the soil. In nature, the nitrates remaining in the soil after the plants have taken them up are reconverted into nitrogen by another class of bacteria, the denitrifying bacteria. Thus, the nitrogen cycle in nature had been kept in balance until the Haber–Bosch process of manufacturing nitrates upset it. The point is that there is as yet no industrial process to reconvert the accumulating nitrates into nitrogen. So, nitrates accumulate in land and aquifers. The planetary boundary of nitrogen cycle has been far greatly exceeded[19]. The deleterious consequences of impairment of nitrogen cycle are: (i) nitrate pollution on land and aquifers, (ii) nitrous oxide ($N_2O$), GHG emission and (iii) exceeding the planetary boundary of the nitrogen cycle. All of these individually and collectively are detrimental to sustainable agriculture and life on Earth.

In the middle of the 20th century, Muller[20] demonstrated the insecticidal action of the dichlorodiphenyltrichloroethane (DDT), and it was readily accepted as an ideal insecticide to destroy a wide spectrum of agricultural and domestic pests. Muller won the Nobel Prize in 1948, but 14 years later, in 1962, Carson[6] in her book *Silent Spring* described the harmful effects of DDT, dieldrin and heptachlor on non-target wild organisms. DDT killed several beneficial, non-target organisms. In the 'web of life' each and every organism has a role to play in maintaining the ecological equilibrium and normal ecosystems services. Notwithstanding their negative dimensions, the inorganic nitrogen fertilizers and chemical pesticides, emerged as 'pivots' (i.e. effective new way to use or exploit nature's endowment) to thwart the Malthusian scourge. These serve as the 'pivots'[3] for a short time, but sooner than later turn into 'hatchets' (i.e. famine, environmental degradation, climate change, etc.) and reactivate Malthusian scourge.

## *Cytogenetics and Mendelian genetics and crop improvement*

The discovery of chromosomes by Wilhelm von Nageli in 1842 preceded the elucidation of the inheritance of characters by Johann Gregor Mendel in 1865. Initially, the role of chromosomes in the division of somatic cells (i.e. mitosis) and the formation of gametes (i.e. meiosis) was elucidated. After the introduction *Drosophila melanogaster*, using genes located on the X-chromosome, the 'Chromosome theory of heredity'[21] was propounded. Location of the genes of the organisms on chromosomes was done using the 'three-point' test and 'linkage maps' of crop plants and vinegar fly were constructed. On the applied side of specific interest to agriculture, the Mendelian laws of inheritance formed the basis of crop improvement through hybridization of plants with different characters and selection of plants recombining the desired traits from both the parents, among the segregating progenies.

In the Indian scenario, in the late 1950s and 1960s, a highly productive and intellectually stimulating period of basic and applied research in genetics and cytogenetics occurred in the Genetics Division (formerly Botany Division) of the Indian Agricultural Research Institute. A team of geneticists such as H. K. Jain, A. T. Natarajan, B. R. Murthy, S. S. Rajan, M. L. Magoon, S. Ramanujam and several others led by Swaminathan had put India on the global map of genetic research. The relevance of basic cytogenetic research to crop improvement had been known since 1940s. However, the studies of Swaminathan on the homology of chromosomes and species differentiation in the genus *Solanum*, section *Tuberarium* at Cambridge University, UK and later at the University of Wisconsin, USA are particularly noteworthy not only in terms of new basic knowledge gained, and novel techniques innovated, but also in developing potato varieties of the sort most needed at that point of time. Some of the trend-setting papers published by Swaminathan are listed in the references 22 to 29. Genome homology studies enabled the transfer of genes for 'frost-tolerance' from wild species *S. acaule* to *S. tuberosum*, and genes for resistance to golden nematode, *Heterodera rostochinensis* from wild species *S. polyadenium* respectively. In the context of making successful crosses between *S. polyadenium* and *S. tuberosum*, a simple surgical technique developed by Swaminathan[29] is of interest. Due to cross incompatibility, the germination and tube-growth of foreign pollen on the stigma was inhibited. Swaminathan solved the problem by removing the stigma, and replacing it with an artificial medium that promoted the germination and growth of the foreign pollen on the stigma which had a biochemical mechanism of cross-incompatibility. This came to be known as the 'Swaminathan artificial stigma' technique and it represents a benign way of overcoming natural barrier to gene exchange, as compared to the present-day recombinant DNA-technology. The simple and elegant technique of Swaminathan assumes enormous relevance today. For instance, Sachs[30] wrote: 'even with all our technological wizardry, we have not yet conquered the Malthusian Challenge since we have not yet adopted a truly sustainable method of feeding the planet', and goes on 'Second, the great agronomic successes since Malthus' time, including the Green Revolution itself, have come at a huge and sometime irreversible, environmental costs'. Had the recombinant DNA technology been used, instead of the 'Swaminathan technique', to develop the frost- and nematode-resistant potatoes, the human health and environmental impacts would have become dominant concerns. Starting from 1920s until late 1960s, plant cytogeneticists have made huge efforts to artificially synthesize polyploids, as had indeed happened in the course of natural evolution. A large number of cultivated crops (e.g. wheat, cotton, sugarcane, groundnut, banana, potato, rice, mustard, etc.) are natural polyploids. The durum ($2n = 4x = 28$) wheat and the vulgare ($2n = 6x = 42$) wheat are example of natural *genomic allopolyploids*. Their diploid progenitors (e.g. *Triticum monococcum*, *Aegilops squarrosa* with $2n = 2x = 14$ chromosomes) are grasses unsuitable for human consumption. In Sweden, Muntzing[31] produced a new polyploidy crop called *Triticale* ($2n = 56$) by crossing wheat (*Triticum vulgare*, $2n = 42$) with rye (*Secale cereale*, $2n = 24$). The rye-wheat spikes were more similar to wheat. This human-made new crop was, however, not so good as the polyploids produced in nature. *Triticale* had partial sterility, and the grains were not as greatly palatable as the natural wheat or rye. Production of triploid fruit crops such as watermelon, to reduce the formation of seeds was more successful. During the 1950s and 1960s, the genetic endeavours for crop improvement focused on radiation-induced mutation breeding. To a lesser extent, chemical mutagens, with some of them acting specifically on the purine and pyrimidine bases of the DNA were also used to induce 'specific' or non-random mutations. The random-acting physical mutagens (gamma-rays, X-rays and neutrons) were, however, more commonly used. Ionizing radiations act largely by inducing 'deletions' (i.e. elimination of a few bases from the DNA) which are, therefore, largely lethal to organisms that are 'strict' diploids (i.e. having only two genomes with very few duplicate genes); on the other hand, the polyploids with several duplicate gene loci are able to tolerate deletions of genes to varying degrees. During the 1950s and 1960s, Swaminathan had developed a globally renowned 'school of radiation genetics' in the Genetics Division of the Indian Agricultural Research Institute. Today, there are over 4000 mutant varieties all over the world. Several of these radiation-induced mutations involve changes in the petal colours of flowers of ornamental plants. Several economically important mutants produced by ionizing radiation in groundnut, green gram, black gram for disease and drought resistance are widely cultivated in India. During the 1950s and 1960s, crop improvement through induced mutations was at its peak. M. S. Swaminathan (India), H. Gaul (Germany) and A. Gustafsson (Sweden), W. Gregory (USA) played a leading role in mutation breeding. In the process, they also elucidated several physical and biological factors which influence both the spectrum and frequency of induced mutations. For instance, Nilan[32] showed how the seed moisture content, oxygen and temperature influenced radiosensitivity of the seeds and also altered the spectrum and frequency of induced mutations. Kesavan and co-workers[33–36] separated the oxic and anoxic pathways of radiation damage and demonstrated that caffeine enhances mutations in the anoxic pathway but substantially reduces the same in the oxic pathway. What have been presented in this section are just illustrative, and not exhaustive.

## Science for breaking the 'yield-ceiling' in wheat and rice

India attained independence in August 1947 in the backdrop of the Bengal famine of 1943–1944. Hence, the first Prime Minister of independent India, Pandit Jawaharlal Nehru had declared that 'everything else can wait, but not agriculture'. The initial steps to enhance the production involved bringing more forest and non-forest land under cultivation, and increasing the irrigation sources. Modifying the genetic endowment of the Indian rice varieties to enhance their responsiveness to chemical fertilizers was first started in early 1950s in the Central Rice Research Institute, Cuttack (CRRI). The science involved was to transfer the genes for 'short stature' of the *japonica* rice to the tall *indica* rice. Swaminathan who was involved in 1954 in the *indica–japonica* crosses at the CRRI, reminisces[37], how the seeds of 'green revolution' were first sown in the rice fields of CRRI, Cuttack, and later in the wheat fields of the Indian Agricultural Research Institute, New Delhi, after obtaining dwarf and semi-dwarf spring wheat varieties (Lerma Rojo–64, Sonara–64, Mayo–64, etc.) from Norman Borlaug who was then at CIMMYT, Mexico. The *indica–japonica* hybridization programme led to the development of a few high-yielding rice varieties which are in cultivation in parts of Tamil Nadu. ADT 27 is one of them.

The fact that the desired kind of dwarfing genes could not be induced in the scientific laboratories using the best of the techniques then available, but nature had come to the rescue by gifting them to plant geneticists should make scientists greatly humbled by the marvels of nature. This has been elegantly explained by Swaminathan himself in a few of his scientific publications and the book '*Wheat Revolution: A Dialogue*[38]'. In order to obtain dwarf/semi-dwarf wheat varieties without also reducing the length of the grain-bearing panicle, Swaminathan and his team of researchers tried three different methods which were then available. One was the inter-specific hybridization involving cultivated *Triticum vulgare* and *T. sphaerococcum* (a short stature plant with compact spike). He also experimented with radiation- and chemical mutagens-induced mutagenesis to induce dwarf/semi-dwarf plants with panicles of normal length. Unfortunately, in all the three cases, the outcome was disappointing since dwarf plants invariably had short, compact spikes too. Short spikes would have fewer grains and hence the yield would be greatly reduced even after chemical intensification of inputs. However, what could not be achieved in the laboratories was provided in nature in the form of 'dwarf stature plants with normal length spike' in *Norin–10* wheat (in Japan) and *Dee-gee-woo-gen* in rice (in China). The nature eliminated the 'pleiotropic' gene effect, which anthropogenic science could not. The dwarf and semi-dwarf wheat in the farmers' fields in Punjab and Haryana revolutionized wheat yields quite substantially. The farmers had never before obtained such record-breaking yield in wheat. Naturally the whole nation was ecstatic in 1967–1968. However, Swaminathan himself was deeply pensive and quite concerned with the long-term consequences of monocropping, excessive application of inorganic mineral fertilizers, chemical pesticides, flooding the soil with groundwater in the name of irrigation etc. In this regard, the relevant part of his Presidential Address[7] to the Agricultural Section of the 55th Session of the Indian Science Congress held in January 1968, in Varanasi, India is reproduced below:

> 'Exploitive agriculture offers great possibilities if carried out in a scientific way, but poses great dangers if carried out with only an immediate profit motive. The emerging exploitive farming community in India should become aware of this. Intensive cultivation of land without conservation of soil fertility and soil structure would lead, ultimately, to the springing up of deserts. Irrigation without arrangements for drainage would result in soils getting alkaline or saline. Indiscriminate use of pesticides, fungicides, and herbicides could cause adverse changes in biological balance as well as lead to an increase in the incidence of cancer and other diseases, through the toxic residues present in the grains or other edible parts. Unscientific tapping of underground water will lead to the rapid exhaustion of this wonderful capital resource left to us through ages of natural farming. The rapid replacement of numerous locally adapted varieties with one or two high-yielding strains in large contiguous areas would result in the spread of serious diseases capable of wiping out entire crops. Therefore, the initiation of exploitive agriculture without a proper understanding of the various consequences of each one of the changes introduced into traditional agriculture, and without first building up a proper scientific and training base to sustain it, may only lead us, in the long run, into an era of agricultural disaster rather than one of agricultural prosperity.'

Within about two decades all that he had foreseen and forewarned had unfortunately come true. Benefits of dramatic increase in productivity (i.e. kg/hectare) were marred by salinization of soil, precipitous fall in water table, depletion of agro-biodiversity especially of the locally adapted famous Punjab varieties of wheat, excessive pesticide use leading to increased incidence of cancers among the members of the farming families etc. On the social dimension, the paradox of 'mountains of grain on one hand, and millions of hungry people on the other' prevailed. In other words, the Green Revolution (exploitative agriculture) which established food security at the national level failed to ensure food security at the individual household level. What this meant was that it did not enhance the resource base in the rural areas to develop on-farm and non-farm livelihoods. Worse of all, the Green Revolution of the 1960s was not sustainable, and it had nothing to do with the 'green economy' in vogue today[39]. Dhillon *et al.*[40] have shown that productivity of wheat and rice has been plateuing since 1996–1997 and this trend has continued through 2007–2008. So, the Green Revolution is going the way the Haber–Bosch process, Paul Mullers's DDT, etc. did!

## Science for sustainable food and nutrition security

### *Background*

With the 'pivot' of Green Revolution beginning to prove itself as a 'hatchet' of food security, the need for a new technology (pivot) to ratchet up food security not just at the national, but indeed at the 'individual household level' had begun to engage the attention of Swaminathan[11,41]. 'The task ahead was to shape science for achieving productivity in perpetuity without accompanying ecological and social harm. It should also pave the pathway to green economy.' Therefore, it just cannot be the same gene-based 'commodity approach' that largely neglected concurrent attention to the physical and biological health of soils, freshwater, biodiversity, renewable energy and atmosphere as well as social and gender inclusiveness. Actually, its design needed to be based on 'systems approach'. And it should be designed in such a way that it adequately addresses both the famines of food (i.e. availability) and rural livelihoods (i.e. access to food).

The new strategy should particularly focus on natural resources conservation, reduction of 'feminization of poverty' in the rural areas, ecoagriculture, ecotechnologies-driven ecoenterprises in the rural areas, as well as skill and knowledge empowerment of the largely unskilled and illiterate rural women and men. Taking all these and several other related parameters (e.g. climate change, environmental degradation, rural poverty, social and gender inequities), Swaminathan[12–16] proposed a 'systems approach'-based strategy, which he called the 'evergreen revolution'. As for its goal, he wrote that it was to 'achieve productivity in perpetuity without accompanying ecological and social harm'. As was elaborated later by Kesavan and Swaminathan[42], degradation of ecological foundations of agriculture and mass exodus of 'environmental refugees' from rural to urban areas to eke out livelihood, feminization of poverty and anti-social activities are all inter-linked, and are also mutually reinforcing. The other consideration is the definition of sustainable development itself as proposed by Gro Harlem Brundtland in the report entitled 'Our Common Future[43]'. The report provided a broad definition of sustainable development: '… development that meets the needs of the present without compromising the ability of future generations, to meet their own needs. It is clear then that sustainable development that takes into account the impact of human activities on the environment and minimizes environmental damage is the key to poverty reduction, ecological security and mitigation and management of weather- and water-related extreme natural disasters.' It is with this clear perception that Swaminathan[14,44] made a plea for transforming Green Revolution into evergreen revolution with these words: 'What nations with small farms and resource-poor farmers need is enhancement of productivity in perpetuity without associated ecological or social harm. The Green Revolution should become an evergreen revolution rooted in principles of ecology, economics and gender and social equity.'

The evergreen revolution is directly relevant to the 'goal of achieving green economy within the context of sustainable development and poverty eradication[45], the major outcome of the United Nations Conference on Sustainable Development (UNCSD), RIO+20 held in Rio de Janeiro, Brazil in June 2012. The emphasis in 2012, 20 years after RIO 92, reveals that the convergence between environmental improvement and economic and social progress has been specially unsatisfactory and that achieving sustainable future will only be possible if the environmental and social pillars of sustainable development are given equal footing within the economic one.

Considering all these, Wilson[46], a Harvard University biologist of rare distinction in his epoch-making book, *The Future of Life*, comes to the conclusion that the evergreen revolution is the best available option to feed the burgeoning human populations and also save the rest of living beings. He wrote: 'The problem before us is how to feed billions of new mouths over the next several decades and save the rest of life at the same time, without being trapped in a Faustian bargain that threatens freedom and security. No one knows the exact solution to this dilemma. Most scientists and economists who have studied both sides of it agree that benefits must outweigh the risks. The benefits must come from evergreen revolution.'

## *Components of the evergreen revolution*

In as much as the evergreen revolution addresses both the production of food and also rural livelihoods in an eco-friendly manner, Kesavan and Swaminathan[47] have described how it has a wide eco-agricultural domain, biovillages for sustainable management of natural resources and on-farm and non-farm livelihoods and VKCs with internet and mobile phone accessories for knowledge empowerment. The biovillages also impart skill empowerment to the unskilled rural women and men to be able to manage ecotechnologies-driven on-farm and non-farm livelihood for income generation and poverty reduction. Details of these are already published by Kesavan and Swaminathan[42,47,48] and are not repeated here.

Kesavan and Swaminathan[49] have described six different evergreen (agro-ecological) types of ecoagriculture. They make a distinction between the purest form of 'organic agriculture' which involves cultivation *without* any use of chemical inputs such as mineral fertilizers and chemical pesticides and the 'Green agriculture' which involves cultivation with the help of integrated pest management, integrated nutrient supply and integrated natural resources management systems. Ecoagricutlure is based on conservation of soil, freshwater and biodiversity and the application of traditional knowledge and ecological prudence. The effective microorganisms (EM) agriculture is a system of farming using effective microorganisms. The 'white agriculture' is a system of agriculture based on substantial use of microorganisms, particularly fungi. The so-called 'one-straw revolution' is a system of natural farming without ploughing, chemical fertilizers, weeding and chemical pesticides and herbicides.

When Kesavan and Swaminathan[42] wrote the paper 'strategies and models for agricultural sustainability in developing Asian countries', they thought that *Bt*-transgenic crops are safe to human health, and environment and that pests would not develop resistance within a very few years and therefore, they suggested that the *Bt* crops could be included in the 'organic agriculture'. However, it is now known more decisively that *Bt*-toxin is *not* specific to alkaline gut, and that the target pest (e.g. *Helicoverpa* sp.) develops resistance under 'selection pressure' much sooner than expected. The papers of Vazquez-Padron *et al.*[50] and Broderick *et al.*[51] dismiss the notion that Cry proteins of *B. thuringiensis* cause lethal effects only in the alkaline gut of Lepidopteran and a few other orders of insect pests. The more recent understanding is that Cry proteins bind to surface proteins of mouse small intestine and permealizes the gut epithelium which then becomes susceptible to commensal bacterial to cause septicemia and death. There are also reports[52–54] that root exudates into the soil from the *Bt* cotton plants exert adverse effects on the beneficial soil microorganisms, earthworms, etc. Kranthi *et al.*[54] have shown that long-term exposure to *Bt*-transgenic crops would lead to development of resistance to Cry proteins due to continuous selection pressure. Considering these, field-evolved resistance to Cry toxins in the pests has been studied both for occurrence and the mechanisms involved[55,56]. The results of these studies raise serious doubts about the usefulness of *Bt*-transgenics in sustainable agriculture. Hence altering their view[42], Kesavan and Swaminathan would now endorse the decision of the International Federation of Organic Agriculture Movement (IFOAM) to ban the genetically engineered *Bt* and Ht transgenic crops from organic and any other form of agro-ecological farming systems. The goal is to keep the agro-ecological systems of evergreen revolution sustainable over long period of time.

There can be really no evergreen revolution without useful gene pools locked up in landraces, indigenous varieties and related species of the cultivated crop plants. Swaminathan's role as a crusader of conservation and sustainable use of biodiversity is evident from his writings and actions over a long period of time. In his Presidential Address titled 'Genetic Conservation: Microbes to Man' at the XV International Congress of Genetics held at New Delhi in December 1983, he pleaded for international efforts involving the *ex situ* preservation of germ plasm by cryogenic gene banks and *in situ* on-farm conservation.

During 1981–1985, as Independent Chairman of the FAO Council, Rome, he played a significant role in getting a Commission on Plant Genetic Resources for Food and Agriculture (PGRFA) and promoting an International understanding that Plant Genetic Resources for Food and Agriculture are a common heritage of humankind. A more ideal approach than cryogenic preservation is the *in-situ* on-farm conservation. In this regard, Swaminathan, through the programmes of activities of the Swaminathan Research Foundation (MSSRF) has established field stations at Kolli Hills (Tamil Nadu), Kalpetta (Kerala) and Koraput (Odisha) to revitalize the conservation traditions of tribal women and also generate economic benefits to them. His elegant idea of conservation, cultivation, consumption and commercialization (4 'Cs') greatly helps in reconciling conservation and development in the farming activities.

The roles of ecotechnologies in the 'biovillage' paradigm for natural resources management and creation of on-farm and non-farm livelihoods with market linkages for income generation and poverty alleviation are described in detail in a paper written in the context of managing extreme natural disasters in coastal areas[48]. Today skills and knowledge constitute the power/strength needed to extricate the rural women and men caught in a web of abject poverty, deprivation and debt-trap. The biovillage (bios = living) harnesses ecotechnologies both for sustainable management of natural resources and enabling self-help groups (SHGs) to manage successfully ecoenterprises such as the production of mud crabs, oyster mushroom, vermicompost, *Trichogramma* egg parasitoid, paper and board from agricultural waste, etc. Biogas production from dung of farm animals provides energy to cook and at the same time neutralizes methane, a potent GHG. As technologies developed based on modern science are invariably double-edged (i.e. they can result in benefit or harm), the MSSRF developed what are called the 'ecotechnologies' by blending frontier science and technologies with traditional knowledge and ecological prudence of the indigenous people, largely tribal women. Because of such blending, the ecotechnologies acquire a pro-nature, pro-poor, pro-women and pro-livelihood orientation. The rural women and men are given training and assisted to build capacity so that they could adopt one of several of the ecotechnologies-based market-driven on-farm and non-farm ecoenterprises. The training is imparted by a pedagogic method of 'learning by doing'. Swaminathan[11] who had thought of this method of training about five decades ago coined the term 'techniracy' to describe it.

As early as 1992–1993, Swaminathan[57] started harnessing the then newly emerged modern information and communication technology (ICT) for providing locale- and time-specific information on a variety of issues required by the rural farming, fishing and landless labour families. As he set up the first few ICT-based VKCs, in a few villages in Puducherry, it became obvious that, especially in the absence of an efficient and timely agricultural extension service, that VKCs could provide locale- and time-specific information on a wide variety of issues and problems faced by the rural people. There are several case studies documented by the ICT staff of the MSSRF on the provision of demand-driven, locale-specific information to the farming, fishing and other rural families which eliminated or greatly reduced the distress and loss of property whether crops on the field or cows and farm animals to supplement income. Broadly, the information demanded by the rural communities and provided in locale-specific manner pertain to weather, crop and animal husbandry, integrated pest management, market prices for local produce, education, hospitals for diagnosis and treatment, transport and other wide-ranging day-to-day problems. Of late, mobile applications have further improved access to women and men in the remote villages, and guiding fishers on their location in international waters or fore-warning them about extreme weather events such as cyclones, etc.

It is emphasized that the unparallel success of the VKCs set up by the MSSRF is not only because of their time- and locale-specific, value-added, demand-driven information content, but also the basic principles of these being user-controlled and user-managed with strong social and gender equities. In fact, the VKCs, like the biovillages, involve a 'bottom-up' and 'participatory' mode of setting-up and management. In order to strengthen the sense of social contract of science, Swaminathan[14,15] had ensured that VKCs establish Lab to Lab, Lab to Land, Land to Lab and Land to Land linkages. An intangible but unmistakable result is that internet and computer literacy made available to young rural women has largely eliminated the shyness and servile attitude, and instead, has empowered them to participate in all the decision-making processes, and make their points of views discussed for appropriate decision and implementation. Swaminathan[15,16] had discussed these in detail. What is novel is that ICT-based VKCs and ecotechnologies-based biovillages are shaping the lives of youth, particularly young rural women. Awe-inspired, one can say that Swaminathan shapes science for rural ecotechnologies and these in turn shape the rural women to face the globalized world with dignity, determination, courage and sensible strategies. Science-based social and gender rejuvenation, conservation of natural resources and their sustainable use as developed and put in place by Swaminathan[12–15,18,44,58] at MSSRF form the strong foundation of sustainable rural development in India and other developing countries. The VKCs have become a movement of the rural women and men and hopefully almost all the 638,000 villages of India would become VKCs before the end of this decade.

## Shaping science for sustainable food and nutrition security

The lessons learnt from the exploitative Green Revolution reveal, among other things, that huge stocks of food materials either locally produced, or imported or dumped do not ensure food security and elimination of hunger of individuals in hundreds of millions of rural households. Such huge quantities of food material could even be let to rot, but not wipe out the pangs of hunger and tears of millions of hungry children and women. They all need to *access* food and for that they need money, which is a function of rural livelihoods. Lack of livelihoods and hence, the lack of purchasing power keep them hungry. Science and technology of ecoagriculture and ecotechnologies-based on-farm and non-farm ecoenterprises with market linkages within the framework of the evergreen revolution has greatly enhanced both the *availability* and *access* to food. There is progress in reducing the number of hungry people in the rural areas. There is, however, still the question of high birth rates (far in excess of the 'carrying capacity' of the region) which unfortunately offsets the gains. In addition, there are the problems of social discrimination and gender inequities. Thus, food security and hunger alleviation at the individual household level require to go beyond the domain of natural sciences and adopt the principles, tools and techniques of social sciences. That is why Swaminathan delves ever so often into social sciences to develop appropriate strategies to achieve the goals of rural poverty reduction, and enhanced food security. What Swaminathan[11–16,18,58] has been emphasizing over the years has now emerged as '*Nature*' editorial[59] under the title, 'Time for the social sciences'. The editorial makes at least two important observations; one is that social, economic and/or cultural factors need to be included in the framing of the questions for research and development (R&D), and other is 'inclusivity' which in the context of the activities of the MSSRF mean 'participatory' and 'bottom-up' approaches. The affectionate philosophy of Swaminathan is that technology should be in harmony with ecology and applied science should include relevant elements of social sciences and gender concerns. In fact, conservation of biodiversity in general, and the agrobiodiversity in particular, is effectively managed by indigenous tribal women based on their traditional knowledge and ecological prudence rather than on esoteric or high-level science-based conservation models. Their methods are simple and effective because they follow how nature works. Nature works on principles of cooperation, symbiosis and common goals with differentiated pathways and strategies in response to changing seasons and mutual feed-backs, whereas the science-based anthropogenic models are based on competition, uniformity than unity in diversity with a strong undercurrent of economic prosperity than ecological integrity. That conservation of biodiversity is absolutely essential for future food security, particularly in an era of climate change has been effectively brought out by Swaminathan in several of his publications[13–16,58,60,61] and illuminating lectures. Considering that global warming-induced climate change would lead to an increase in the average daily temperature, sea level rise and consequent salinization of the coastal soil and aquifers, extreme hydro-meteorological events (e.g. cyclones, downpours causing floods, long spells of drought, etc.) and altered monsoon patterns, Swaminathan[58,60] has noted the importance of genes for salinity and drought tolerance, submergence tolerance, and higher temperature tolerance. It would be prudent to look for genes in the closely related variants (i.e. indigenous varieties, landraces, closely related subspecies, etc.) so that Mendelian breeding could be undertaken. The molecular marker-assisted selection procedures of breeding would be of great advantage.

On the social, economic and national dimensions, India ranks 55 among 76 countries on the Global Hunger Index (GHI). The GHI developed by the International Food Policy Research Institute (IFPRI) is based on three criteria, viz. (i) undernourishment which is the proportion of undernourished people as percentage of the population, (ii) child underweight, which is the proportion of children under the age of five who are underweight due to undernutrition, and (iii) child mortality which is the mortality rate of children under the age of five largely due to hunger and starvation. Of the three kinds of hunger, viz. *undernutrition* (inadequate consumption of calories), *protein hunger* (inadequate consumption of pulses, milk, eggs, meat, etc.) and *hidden hunger* (caused by deficiency of micronutrients such as iron, iodine, zinc, vitamin A, vitamin B12, vitamin D, etc.), the GHI is largely based on undernutrition. Even if the hidden hunger leads to debilitation, morbidity and then death, it could be mistaken as due to undernutrition. This is so because, as the term implies, the hidden hunger caused by microdeficiency is not readily discernible. Therefore, in several of his lectures and publications, Swaminathan[15,58,62–67] specifically points out the need to address the micronutrient deficiency. The UN Secretary–General, Banki-Moon launched at the Rio de Janeiro in 2012, a 'Zero Hunger Challenge' with a target date of 2025 for the elimination of hunger, malnutrition and food insecurity. The five pillars of the zero hunger challenge are: (i) 100% access to adequate food all year round; (ii) zero stunted children less than 2 years of age; (iii) 100% increase in smallholder productivity and income; (iv) all food systems to be sustainable; (v) zero loss or waste of food. Without achieving the zero hunger challenge, sustainable development is not possible. Immediately following the declaration of 'Zero Hunger Challenge', Swaminathan wrote an editorial in *Science*[65] on 'Combating Hunger'. In this editorial, he refers to the High Level Panel of Experts to the United Nations on World Food Security that was Chaired by him. The panel released a comprehensive report on 'Social Protection for Food Security' to combat chronic childhood hunger. It recommended the concept of 'food security floor', which recognizes that freedom from hunger is fundamental human right, defining the minimal steps (i.e. nutrition literacy, clean drinking water, sanitation and primary health care) needed for hunger elimination. Two years later, the UN designated '2014 as the International Year of Family Farming' recognizing that about 500 million family farms of varying sizes, involving over 2 billion people, play a key role in food production and food security worldwide. Writing yet another editorial in *Science*[66] on 'Zero hunger', Swaminathan suggested that family farming, characterized by diversified crops, can be harnessed to support nutrition-sensitive agriculture. Noting that commercial farming tends to promote market driven monoculture of food crops, which ignore nutrient needs, the family farms, both small holder as well as bigger ones can cultivate diverse crops with nutrient content specific to eliminate a deficiency. Kesavan and Swaminathan[67] elaborated as to how the evergreen revolution with several elements of family farming can cultivate crops identified for their specific nutrient content to provide agricultural remedies to nutritional maladies in different agro-ecological regions.

Swaminathan and his team of experts in food and nutrition security[68] have proposed a farming system model to leverage agriculture for nutritional outcomes, called 'farming system for nutrition (FSN)'. It is perhaps the most simple in design, yet highly effective to provide agricultural/horticultural remedies to nutritional maladies in a given agro-ecological region. In fact, it is the nutrition-sensitive agriculture. Quite recently, Swaminathan[62] has discussed the strategies to overcome the three major forms of hunger, viz. 'under nutrition', 'protein hunger' and 'hidden hunger'. To eradicate protein hunger, he has shown the effectiveness of promoting the concept of 'Pulses Panchayats' to encourage cultivation and consumption of pulses in villages. The table 2 (horticultural remedy for nutritional malady) in his paper[62] provides a list of horticultural plants that can provide remedy to nutritional maladies caused by nutrition deficiencies of proteins and micronutrients such as vitamin A, vitamin C, vitamin B as well as zinc, iron, iodine, etc. Further, he brings into it 'community hunger fighters' to master the science and art of leveraging agriculture for nutrition. Swaminathan[62] also recommends that the existing kitchen gardens should be redesignated as 'nutrition garden' growing spinach, banana, cabbage, tomato, sweet potato, beetroot, carrot, lettuce, etc.

Science has shown the way to achieve food and nutrition security in hundreds of millions of small and marginal farms, many of which are ideally the smallholder family farms. Good governance and policy support are essential to translate the 'know-how' and 'do-how' into field-based realities. In addition, it is also essential to keep the human population at a level that the already depleted resources can somehow be sustainably used. The 'ecological overshoot'[69] is a major threat to sustainable food and nutrition security. 'Ecological footprint' and its overshoot largely require public policy and people's cooperation. Technology has, unfortunately, no quick fix, and in fact, several of the technologies actually contribute to human overshoot of the ecological footprint. This would be evident from the way the consumer products are generated and dumped.

## Agricultural research in an era of climate change

Swaminathan and Kesavan[70] point out that human-induced changes in climate will have both common and differentiated impacts. Hence, the climate risk management research and training centres should be established in all agro-climatic zones. Particular attention should be given to establish 'gene banks' containing genetic resources for a warming planet.

Global warming threatens food security in many ways. About 12,000 years ago, the average global surface temperature was about 10°C. The $CO_2$ levels in the atmosphere were much lower, but not exactly known. The best estimates suggest that it was about 200 ppm. Over a period of next 5000 years, the average global surface temperature gradually rose to an average of about 15°C, where it remained until about 100 years ago. Then the human activities, including the early acceleration of agricultural activities exerted an appreciable effect on the functioning of the Earth System via an increase in atmospheric $CO_2$ concentration, but it was still operating within the Holocene state[71]. With the ushering in of the industrial revolution in 1780, fossil fuel-based human activities progressed very rapidly and also intensely. The 'holocene', the relatively warming period of about 10–11 millennia should have ended and the next glaciation period ought to have started; but that certainly is *not* the case. In fact, the global warming has been speeding up. Visualizing that this situation is novel in its speed, its global scale, and its threat to the resilience of the Earth System, the Nobel Laureate Paul Crutzen coined the term 'Anthropocene'[1] to the present, in many ways human-dominated geological epoch, supplementing the 'Holocene'. Steffen *et al.*[71] go further to note that Earth has left Holocene, and has entered a new geological epoch 'Anthropocene' that risks driving the Earth System onto a trajectory toward more hostile states beyond redemption. Zalasiewicz *et al.*[72] discuss how the humanity itself has become a global geophysical force, equal to some of the 'great forces of Nature' in terms of Earth System functioning. If so, can science be shaped to counter the 'anthropocene', and let the Earth re-enter its natural cycle, i.e. glacier period? The answer is that it is difficult, but human ingenuity can, provided the humans forget their differences and unite as one species to save the planet Earth and humanity.

While the aforementioned impress the gravity of global warming-induced climate change, Swaminathan and Kesavan[70] sum up the detrimental consequences of global warming which are multidimensional and interrelated as follows:

- Unpredictable deviations in monsoon behaviour.
- Freshwater scarcity and higher evapotranspiration.
- Receding glaciers and drying up of perennial rivers like Ganges, Yamuna, Brahmaputra, etc.
- More frequent incidence of extreme hydro-meteorological events (cyclones, hurricanes, typhoons, floods and droughts, etc.) with increased destructive potential.
- Emergence of widely different pests causing severe damage to crops, infectious diseases, epidemics, etc.

Indian agriculture normally referred to as a 'gamble with monsoon' would become even more weather behaviour vulnerable.

Vulnerability of agriculture has ecological and physiological dimensions. The ecological effects include those on soil, freshwater and biodiversity. The arid and semi-arid areas of the tropics in Africa and South Asia and in the Mediterranean climate of West Asia and North Africa will be extremely vulnerable. Some of the adverse effects which need scientific checkmating[70] are the following:

- Loss of soil organic matter; small farms must manage soil nutrients by using farm yard manure, ploughing in stem-nodulating *Sesbania rostrata*, biofertilizers, etc. Agro-forestry systems involving fertilizer tree such as *Feidherbia albida* will also help.
- Higher air temperatures are likely to accelerate the natural decomposition of organic matter, which is beneficial.
- Rainwater harvesting, storage and sustainable use.
- Favourable conditions for the proliferation of insect pests and vector-borne diseases. Models on plant diseases indicate that climate change could alter stages and rates of development of certain pathogens, modify host resistance, and result in changes in the physiology of host–pathogen interactions.
- There are several reports that increased $CO_2$ concentration in the atmosphere increases photosynthetic efficiency, and biomass of crop plants, forest trees and other plant species[73–75], important crop plants such as rice[76], wheat[77], sorghum[78] and cotton[79]. As of now, the $C_3$ plants such as wheat, barley, rice and potatoes are known to respond positively to $CO_2$ enrichment. However, as has been pointed out by Sinha and Swaminathan[80], the rise in temperature would nullify the benefit of higher $CO_2$ concentration. In wheat, there is an adverse impact on yield when the mean temperatures rise by 1 to 2°C. For each 0.5°C increase in temperature, there would be a reduction of crop duration of seven days, which in turn would reduce yield by 0.45 tonnes per hectare. Swaminathan and Kesavan[70] observe that for India as a whole, rice may become even more important than now in the national food security system since rice unlike wheat can give high yields under a wider range of growing conditions. For example, rice grows under below sea level conditions in Kuttanad in Kerala, as well as in high altitude regions in the Himalayas. The amplitude of adaptation is high in rice. Further, water-requirement of paddy is known to be greatly reduced through system of rice intensification (SRI).

The science of crop management to reduce the adverse impact of climate change needs to be more vigorously pursued. However, the role of community management of climate change has been appropriately emphasized by Swaminathan[15,18,41,58]. The VKCs of MSSRF are providing weather and crop-related data to the rural communities. Swaminathan, in a series of above said publications and several popular writings in media like *The Hindu* has pleaded for training and capacity building for one woman and one man in every village, for tackling climate risk-related events. The women and men so trained are called the Community Climate Risk Managers. Such managers will be familiar with the art and science of managing climate risks like drought, flood, sea level rise, higher temperature, etc. The climate risk managers are trained to manage good weather code, drought code, flood code, etc. The good weather code involves maximizing the benefits of good harvest because of a good monsoon, adequate soil moisture, etc. The drought code includes necessary strategies to minimize the adverse impact of drought and a flood code to prevent excessive distress and damage and to promote a post-flood production plan. The drought code also involves cultivation of low water requiring, but high value crops like pulses and oilseeds. Swaminathan[18] prescribes the following for climate resilient management of agriculture in India:

(a) Conservation farming and climate resilient agriculture in Punjab, Haryana and Western UP in order to defend the gains already made through Green Revolution.
(b) Bridging the gap between potential and actual yields in Eastern India through integrated packages of technology, services and public policies.
(c) Launching a pulses and oilseeds revolution in rainfed areas through organization of pulses and oilseeds villages.
(d) Launching a post-harvest technology and value-addition revolution through ending the prevailing mismatch between production and post-harvest technologies and by promoting agro-processing and agribusiness.
(e) Bringing about a management revolution leading to equipping small and marginal farmers with the power and economy of scale.

While these are all management issues to achieve climate resilient agriculture, the conservation of biodiversity is the most fundamental key to development of varieties and breeds that can tolerate climate change risks. The suggestion of Swaminathan[61] in 1983, for a permafrost facility to preserve germ plasm was realized in 2008 in the form of 'Svalbard Global Seed Vault' set up by the Norwegian Government, but managed jointly by the Norwegian Ministry of Agriculture, the Global Crop Diversity Trust and the Nordic Genetic Resource Centre. Located in the village of Longyearbyen on Svalbard island located at 78° north in Arctic circle, space has been created to store sample seeds of 4.5 million varieties. The vaults have a natural temperature of –4°C round the year, which has been further lowered to –18°C, the optimal temperature for long-term seed viability. The Svalbard *ex-situ* preservation of millions of cultivars is indeed Noah's ark to serve as safety net for food security in the era of global warming and climate change. Swaminathan[81] brings out the importance of gene banks for future food security of a warming planet.

## Concluding remarks

Had there been no advances in science and science-based technologies, Malthus would have been proved right a long time ago. Yet, the fact remains that science and technology can do no wonder without natural resources which are finite and are undergoing depletion and degradation rapidly. Inter-generational inequities for natural resources would put the future generations at a great disadvantage to find resources for their own development. Some of the technologies which more than century ago helped in developing agricultural inputs to achieve dramatic yields have now become the very cause (hatchet) of environmental degradation, depletion of biodiversity, impairment of ecosystems services, etc. All these should open our eyes to appreciate that transformation of the Green Revolution (i.e. exploitative agriculture) into an 'evergreen revolution' that pays concurrent attention to the integrity of the ecological foundations of sustainable agriculture, social and gender equities, should not be delayed any further. It would be appropriate to conclude this paper by referring to Swaminathan's book[82], *In Search of Biohappiness – Biodiversity and Food, Health and Livelihood Security*. Among the other things, he refers to Conservation, Cultivation, Consumption and Commerce (the 4 Cs) together constituting the pathway to biohappiness. Science has a major role to play, but not without close interaction with social sciences.

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