Review:

Green Revolution: Pathways to Food Security in an Era of Climate Variability and Change?

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Critical technological breakthrough in agriculture and the policy surrounding it resulted in a series of successes in increasing the food productivity, especially in developing countries, and came to be known as Green Revolution. The systems of food production, however, to date, faces new challenges due to convergence of multiple factors, including the impending threat of changing climate. Our goal in this paper is to review and reflect upon the achievements of the Green Revolution, perceived as a superb achievement of science and technology policy in South Asia and elsewhere, and discuss how the program and the policy that came to be associated with it will respond to new challenges. We argue that in an era of rapidly changing climate and the uncertainties associated with it, the world food system is encountering a significant challenge leading us to question whether the Green Revolution celebrated as technically advanced and "modern" in the past is adequate to respond to the diverse array of challenges that will be encountered in the 21st century. For all its innovativeness and achievement, the ability of the Green Revolution to respond to emerging challenges is unlikely to follow a smooth trajectory with time. So responding to emerging challenges requires a new gestalt of concepts that demands different science and technology policy whereby farmers can produce more food and other agricultural commodities sustainably under conditions of declining per capita arable land, irrigation water, dwindling resource base and agricultural labor supply along with the stresses of climate change.

Keywords: food security, Green Revolution, climate change, science and technology policy

1. Introduction

During the second half of the 20th century, the world in general, made remarkable progress in the production of food and fiber, allowing a decline in the proportion of hungry population. The decline was remarkable given the fact that the global population had more than doubled (Godfray et al., 2010 [1]). One of the major attributes that contributed to the progress in food production came from the technological breakthroughs in agriculture that began around the mid 20th century. By breeding rust-resistant wheat varieties at the International Maize and Wheat Improvement Center (CIMMYT) in Mexico, the late Nobel Prize laureate Norman Borlaug successfully catalyzed a global effort in controlling wheat rust, which until then had perennially threatened wheat growers around the world. As a result, about 117 million ha of land under wheat cultivation were protected from wheat rust, directly ensuring the food security of 60 to 120 million rural households (Dubin and Brennon, 2009 [2]). This breakthrough resulted in what became known as the Green Revolution (Hazell, 2009 [3]), and is credited with increasing crop yield, decreasing food prices, and increasing calorie intake of the global population (Khush, 1999 and 2001 [4]).

The Green Revolution was mutually reinforced by a complex policy that included but was not limited to extension services, input subsidy, marketing of agricultural products, and the new found farmers' enthusiasm [5] towards the science and technology policy. This policy based on the science and technology of Green Revolution and designed to help it succeed eventually gave rise to national and international institutions such as the National Agricultural Research Systems (NARS) and the International Agricultural Research Centres (IARCs) of the Consultative Group for International Agricultural Research (CGIAR) (Evenson and Gollin, 2002 and 2003 [6]). These institutions have been instrumental in devising agricultural development policies that have been the bedrock of the Green Revolution. Such science and technology policies are, to date, routinely designed and executed by NARS and IARCs, and the continuous deployment of the Green Revolution technologies and the success it has gained thereafter has been considered to be natural outcomes of such institutional arrangements [7].

However, the success of the Green Revolution was not

uniform across geographic regions, and its outcomes were mixed. Most importantly, it was not able to eradicate hunger in countries where it was introduced and practiced the most (e.g., South Asia). To date, access to food or food security, as it is more commonly called now, remains an unfulfilled dream for about 925 million people worldwide (Food and Agricultural Organization [FAO], 2009 [8]). Food security involves physical, economic, social, and environmental access to a balanced diet and clean drinking water for everybody (Swaminathan, 2010 [9]). Physical access is a function of the availability of food when needed. Economic access is related to purchasing power and employment opportunities, where as social access is conditioned by gender equity and justice, and environmental access is determined by sanitation, hygiene, and clean drinking water. Moreover, loss of biodiversity and damage to ecosystem is taking place at a rapid pace and has the potential for serious implications in terms of our capacity to deal with new challenges rising from climate changes. Thus, ensuring food security entails a holistic approach involving food and non-food factors, which Swaminathan (2010 [9]) describes as an "evergreen Green Revolution."

Recent studies have indicated that the global food system over the next 40 years will experience significant pressure due to convergence of multiple factors. On the demand side, the current population will increase from nearly 7 billion to over 9 billion by 2050 (Lutz and K.C., 2010 [10]), a growth that would require farmers to increase food production from nearly 6 billion tons (gross) to 9 billion tons by 2050 (Borlaug and Carter, 2005 [11]). On the supply side, competition for land, water, and energy will intensify along with the need to curb many negative impacts of agriculture to environment (Millennium Ecosystem Assessment Report [MA], 2005 [12]; Millennium Development Goals [MDG], 2005 [13]; Scherr and McNelly, 2008 [14]). Food security has been further strained by the growing volatility of the food market notably during 2007-2008 (von Braun, 2010 [15]), political controversy surrounding the use of grain to produce biofuels (Abbott et al., 2008 [16]; Pretty et al., 2010 [17]), and the increasing demand for meat and dairy products due to increased global wealth and purchasing power (Foresight, 2011 [18]). Any one of these factors will be likely to pose significant challenges, but together they could constitute a major threat to the global food security. Overarching all of these issues is the impending threat associated with the uncertainty of changing climate and its consequences in global and regional food production (Easterling et al., 2007 [19]).

Farmers everywhere in the world remain vulnerable to climate and other ongoing changes. The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) concludes that the Earth is committed to at least as much warming over the next 90 years as was experienced over the previous century, even if greenhouse gas (GHG) concentrations were immediately curtailed to 2000 levels (IPCC, 2007 [20]). Multiple climate model simulations show the potential for accelerating changes in climate with significant shifts in interannual variability (MacCracken et al., 2003 [21]; Stainforth et al., 2005 [22]). And, while the average climatic conditions may be changing more or less monotonically, seasonal and interannual variability may be highly unstable, creating extreme climatic conditions. The impact of extreme climatic conditions on crop productivity is likely to be far greater than the effects associated with the average change in climatic conditions (Mearns et al., 1997 [23]). Therefore, the ability of agricultural systems to adapt to climate change is unlikely to follow a smooth trajectory with time (Chhetri et al., 2011 [24]), mainly due to the unpredictable nature of climate change and the lack of strong institutions and appropriate technologies to tackle the problem of climate change (Agrawal, 2008 [25]).

Wide ranging estimates of how these changes will impact agricultural production gives the urgency to address adaptation more coherently, particularly because of agriculture's sensitivity to climate change and variations (Howden et al., 2007 [26]). For example, a moderate warming in temperate regions is associated with marginal increases in yields, especially if assumptions about some level of adaptations by farmers are factored into the models. In more than 40 developing countries, mainly in sub-Saharan Africa and Asia, cereal yields are expected to decline with mean losses of about 15% by 2080 (Fischer et al., 2005 [27]). In areas where the temperatures are already close to the physiological maxima for crops, such as seasonally arid and tropical regions, higher temperatures may be more immediately detrimental, increasing the heat stress on crops and water loss by evaporation (Easterling et al., 2007 [19]). For example, increase in the minimum temperature during the rice and wheat seasons increase the respiration requirement leading to reduction in the net productivity by shortening the time required for maturity (Lal, 2011 [28]). Studies conducted at the International Rice Research Institute (IRRI) in the Philippines also show that a 1°C increase in nighttime temperature can cause rice yield to decrease by as much as 10% (FAO, 2005 [29]).

The role of science and technology in agriculture's ability to meet food demands has come to special global attention in recent years, especially in response to jumps in global food price, dwindling harvest, and threats of climate change (World Bank, 2007 [30]; Royal Society, 2009 [31]; National Research Council, 2010 [32]). Increasingly, it has become clear that the science and technology that guided the Green Revolution in the past may not be the optimal solution at present and in the future given the convergence of the multiple factors discussed above. This poses a significant challenge to the development of regional, national, and local agricultural policies that support sustainable and efficient agricultural practices. Although there has been substantive discussion of negative externalities of the Green Revolution, very little has been explored about how the technologies lent by it would respond to changes led by climate variability in the future. Previous studies of the Green Revolution have mainly limited themselves to highlighting the advantages

and drawbacks of technologies and inputs accompanying them. Our goal in this paper is to review and reflect upon the achievement of the Green Revolution in agriculture, perceived as a superb achievement of science technology in agriculture during the second half of 20th century, and discuss how this system will respond to new challenges emerging in light of the climate change in future. This paper will reflect on both the success and failure of the Green Revolution to highlight the debate on the culture and practice of the science and technology policy from the prism of current food security reality. We also argue that the Green Revolution technologies, in its current form, may not be able to cope with the shock and stress emanating from climate variability and change. We further argue that it is in this premise that adapting to climate and other ongoing changes require a new gestalt of concepts, i.e., not merely a movement from one form of technology to another, a simple flow from green to evergreen revolutions. It needs a different science and technology policy, whereby farmers can produce more food and other agricultural commodities sustainably under conditions of declining per capita arable land, irrigation water, dwindling resource base, and agricultural labor supply, along with the stresses due to climate change.

In the following section, we will review the salient research that outlines both the success and concerns of the Green Revolution. This section also reveals the concerns surrounding climate change and its impacts on food security of developing countries. In section 3, we will detail the arguments for alternative to current Green Revolution technologies. Just as it is imperative to endure policy decisions informed by sound science, it is also vital that the science be relevant to the needs and issues of farmers operating in different social, cultural, and environmental conditions. In addition to raising concerns about the ability of the Green Revolution to continue to produce food without compromising the environment quality, this section highlights the need for farmers and their supporting institutions to become proactive rather than be reactive. In the final section, we justify the rationale for different levels of thinking and planning that are required for improved adaptation to a changing climate.

2. Green Revolution: A Review

Green Revolution is characterized by the development and diffusion of high yielding varieties (HYVs) of crops, expansion of irrigation to assure the timely supply of water, multiple cropping in a year made possible by early maturing HYVs, and the use of agrochemicals. The widespread use of HYVs, primarily wheat and rice, by farmers in Asia and Latin America during the early 1960s marks the beginning of the Green Revolution (Matson et al., 1997 [33]). It is credited for exceeding the per capita grain production as presented in the *Global 2000 Report to the President*. According to Evenson and Gollin (2002 [6] and 2003 [7]), without the Green Revolution the world food and food grain prices (weighted by production) would have been 18-21% higher, and the world food production would have been 4-5% lower. They contend that the area planted to cropland would have been significantly higher without the adoption of HYVs, whereby the total acreage would have expanded by 5-6 million ha in developed countries and 11-13 million ha in developing countries, at the cost of natural forest and shrubland. In terms of dietary impact, they calculated that the average reduction in caloric availability per capita of the global population would have been 4.5-5% lesser in developing countries (and about 7% lower in the poorest regions), and approximately 13-15 million more children, predominantly located in South Asia, would have been malnourished and infant mortality would have been higher.

The expansion in crop productivity was impressive as indicated by the increase in average cereal production in South Asia from 147 Mt in 1980-1981 to 239 Mt in 1999-2000, largely due to the rise in productivity (Broca, 2002 [34]). In the Indo-Gangetic plains of South Asia, the yield and production of rice and wheat registered an all time high during the 1970s and 1980s (Sinha, 1997 [35]). The Green Revolution allowed countries like India to eliminate the fear of famine and concentrate on developing other sectors of the economy (Conway, 1997 [36]) and position the country to become one of the largest agricultural producers in the world (Smit and Wandell, 2006 [37]).

As mentioned earlier, the outcomes of the Green Revolution is mixed. One of the best-known earlier reviews by Keith Griffin (1974 [38]) painted a grim reality of HYVs, whereby he argued that there had been no Green Revolution in rice. Subsequent studies pointed to the issue of disparities in infrastructure development and investment within and between countries leading to unequal outcomes (Prahladachar, 1983 [39]; Lipton and Longhurst, 1989 [40]). The adoption of Green Revolution technologies in the 1970s and early 1980s, and the recognition that they favored larger farmers prompted the analysis of new forms of social differentiation among farmers, including the conflict between "adopters" and "non-adopters," and contributed to deteriorating labor conditions as HYVs was labor-displacing (Thompson et al., 2007 [41]). Holt-Gimenez (2006 [42]) argues that the high cost of purchased inputs deepened the divide between large farmers and smallholders, because the latter could not afford the technology. The Green Revolution's expensive "packages" favoring a minority of economically privileged farmers that led to further concentration of land and resources.

In the early 1980s, farmers and experts started noticing the negative consequences of pesticides and fertilizers in the local ecosystems, and the Green Revolution came to be considered as one of the causes of the environmental disaster of modern times (Shiva, 1993 [43]). The debate further intensified when researchers and practitioners started to point out the consequences of the water-thirsty Green Revolution technologies on groundwater levels across India (Swaminathan, 1993 [44]). Unfortunately, ecologically unsound public policies, like the

supply of free electricity, led to the over-exploitation of the aquifer in the Punjab, Haryana, and Western UP region (Kesavan and Swaminathan, 2006 [45]). To date this heartland of the Green Revolution is in deep ecological distress (Jackson and Hobbs, 2009 [46]). Significantly, the increasing trend of suicides by farmers in the mid-1990s unleashed a series of debate in India associating the Green Revolution with social and economic failure (Jishnu et al., 2010 [47]).

Researchers have also raised concerns about the Green Revolution's lack of focus on crops grown in marginal areas by a large number of farmers (Swaminathan, 2010 [9]). In the areas where water is a limiting factor for agriculture, farmers have not been able to take the advantage of the Green Revolution technology for even rice and wheat. Scientists have tried and failed to develop high-yielding crop varieties for most marginal environments, where water, climate, and soil constraints cannot be overcome through varietal improvement (Lal, 2011 [28]). Yield gains that were achieved during the Green Revolution have begun to erode due to environmental degradation and other effects of unsustainable production (Shiva, 2008 [48]). Social and environmental issues associated with the Green Revolution raises important questions about whether the form of agriculture developed and promoted during the second half of the 20th century, celebrated as "modern" and technologically advanced, remain viable enough to respond to the emerging challenges of the 21st century (Thompson et al., 2007 [41]).

Compounded by climatic anomalies such as the poor monsoons of late 1970s and early 1980s, which significantly impacted rice harvest across Asia, farmers and a small number of researchers and policymakers began doubting whether the Green Revolution was really a sustainable solution for food security in the future (Jishnu et al., 2010 [47]), especially in an era of changing climate. The AR4 of the IPCC provides strong evidence that the Earth's climate is changing and that much of this change is very likely (more than 90% confidence level) due to the increase in concentration of GHGs associated with human activities. This change is evident from observations of increased global average temperature of 0.74°C (±0.18°C) over the past century, altered precipitation patterns, declining snow cover, and increased global average sea level of 1.8 mm (±0.5 mm) per year (IPCC, 2007 [20]). Based on the compiled historical surface temperature data from tree rings, marine sediment, ice cores, and other sources, Mann et al. (2008 [49]) provide further evidence that the observed average global temperature is at an all-time high. Some of the most profound and direct impacts of climate change over the next few decades will be on the systems of food production (Easterling et al., 2007 [19]). Although considerable uncertainties remain as to when, where, and how the climate change affects agriculture, a recent study by Lal (2011 [28]) shows a net decline of cereal production by 4-10% in South Asia by 2050. The vulnerability of agriculture to climate change also comes from factors associated with socioeconomic, political, and technological conditions limiting the farmers' ability to adapt to change.

The diversity of perspectives from which the Green Revolution has been analyzed is impressive, and the literature on it can never be monocultural. It has come face-to-face with many perceived social and environmental ills. At the heart of the debate is the issue of governance of science and technology and the question of equity, poverty, social justice, environmental externalities, and social exclusion (Thompson et al., 2007 [41]). While the Green Revolution symbolizes the power of modern science and technology and reinforces its belief about the inadequacy of traditional knowledge to create the scales and the levels of productivity required to feed the growing population of the world, the lack of new advancement in agriculture is raising new concerns (Jishnu et al., 2010 [47]). Farmers and their supporting institutions are continually being challenged to develop crop varieties that can resist diseases and insects, tolerate extended drought, and are able to yield satisfactorily during times of climate distress (Borlaug, 2007 [50]). This has to be achieved on a shrinking agricultural land base, with minimum impacts on the local environment, and in climate that is not the same as was in the past. More than half of the world's 924 million hungry people are smallholder farmers and cultivate on marginal lands. New science and technology policy will also have to address the needs of these farmers and the Green Revolution, as we know it, has yet to fully realize this.

3. Green Revolution Technologies in the Face of Climate Variability and Change

The continuing deterioration of natural resource base essential for sustaining food security – land, water, agro-biodiversity, and forests – is leading to stagnation in crop yields in many regions of the world. According to Swaminathan (2010 [9]), an analysis of food security indicators in rural India carried out by the M.S. Swaminathan Research Foundation (MSSRF) with support from the World Food Programme (WFP) indicates that India's food basket (Punjab-Haryana region) may become food-insecure by the early 2030s. Some of the indicators used by MSSRF in measuring sustainability of food security were land degradation and salinization, extent of forest cover, groundwater depletion, and nature of crop rotation. In all of these parameters, the Punjab-Haryana region ranked lower than that in other states of the country. The common rice-wheat cropping pattern that was introduced in the 1960s as part of the Green Revolution led to displacement of grain and fodder legumes capable of maintaining soil fertility. The study also reveals that the application of the Green Revolution techniques that is primarily based on land and water mining is unsustainable, and climate change may compound such problems with adverse effects brought about by changes in temperature, precipitation, and sea-level rise.

Intensive cultivation of land with the heavy use of chemical fertilizer, as is the case with the Green Revolu-

tion, would gradually deteriorate the productive capacity of the land. Likewise, the indiscriminate use of agrochemicals such as pesticides would continue to have adverse impacts on agrobiodiversity as well as on human health through the toxic residues present in grains and other edible crop parts (Jackson and Hobbs, 2009 [46]). Excessive mining of underground water to fulfill the irrigation needs of the Green Revolution agriculture would lead to exhaustion of groundwater resources (Swaminathan, 2006 [51]). Replacement of locally adapted crop varieties with 1 or 2 high-yielding strains in large contiguous areas would result in the spread of serious diseases capable of wiping out the entire crop population (Swaminathan, 1993 [44]). In an era of rapidly changing climate and the uncertainty associated with it, the continuous practice of Green Revolution in its current form has the potential to weaken the adaptive capacity of farmers.

More than any other factor, the summer monsoon plays a critical role in the success of agriculture in South Asian countries, including Bangladesh, Bhutan, India, Nepal, and Pakistan, which constitutes more than 22% of the world's population (Dhar and Nandargi, 2003 [52]; Challinor et al., 2003 [53]). The summer monsoon is highly variable, across space and time, and exerts a strong influence on the supply of water resources and associated activities. The summer monsoon rainfall is responsible for 50% of the variability in total grain production anomaly in the region (Planning Commission, 2001 [54]). For example, in India, during the years of deficient monsoon (1966, 1972, 1974, 1979, 1982, and 1987), food grain production declined correspondingly, while during the years of excess or normal monsoon (1970, 1975, 1978, 1983, and 1988) productivity was comparatively high (Lal, 2011 [28]).

Given the significance of monsoon rainfall to South Asia, its response to climate change is an issue of both scientific and societal importance. In their studies, Ashfaq et al. (2009 [55]) found an overall suppression of summer precipitation, delay in monsoon onset, and increase in the occurrence of monsoon break periods during the 21st century. This could have had substantial impacts in the agricultural production of these countries. Studies also reveal that by 2025, there will be a shortfall of more than 20 million Mt of rice and wheat, the major staple food crops of the region (FAO, 2005 [29]). This raises an important question on whether the current form of agriculture that is celebrated as "technically advanced and modern," is able to respond to the diverse array of challenges that they will encounter while moving forward. This argument arises from the following considerations:

1 Continuous use of the Green Revolution technologies debilitates **local knowledge and adaptive capacity of smallholder agriculturists** and exposes them to the risks associated with climate change and subsequent uncertainty

2 Green Revolution leads to **loss of agrobiodiversity**, the basis for maintaining **resiliency, livelihoods, food security,** and regional environmental sustainability

3 In an era of competing use of water punctuated by uncertainty of its supply, water demanding agricultural system, the hallmark of Green Revolution, faces more challenges ahead

4 Smallholder farmers are currently facing **new and multiple challenges**, and they are substantially different from those encountered a few decades ago

5 Livelihoods and food security in an era of changing and uncertain climate **require robust adaptation planning** and the science and technology policy is ill equipped to do so.

3.1. Local Knowledge and Adaptive Capacity of Smallholder Agriculturists

By incorporating the best characteristics of individual plants through continuous selection, over the millennia, farmers have developed dynamic and complex systems of agricultural practices and have accumulated intricate knowledge associated with those practices (International Plant Genetic Resources Institute [IPGRI], 1997 [56]). The science and technology policy associated with the Green Revolution, which emphasizes only on the yield dimension of crops, does not seem to be able to explain, let alone respond to the complexity, diversity, and uncertainty of the livelihoods of small farmers who operate in diverse and risk prone settings where surprises are inevitable and must be anticipated (Chambers, 1991 [57]). What is needed is the ethnographic understanding of place-specific adaptation processes (Jasanoff, 2005 [58]), harnessing of the knowledge systems of farmers locked-in across cultures and practices (Chhetri and Chhetri, 2010 [59]), and the social and political dimensions of institutions and governance (Scoones et al., 2007 [60]). This requires policies and actions that not only contribute to social objectives like food security for growing population, but also enriches our understanding of the evolving cross-scale ecological, social, economic, and political conditions that provide flexibility in adapting to surprises and change (Thompson et al., 2007 [41]). It is in this premise that we question how the ability of science and technology policy associated with the Green Revolution – that are not designed to address surprises – absorb perturbations and can surprisingly make a smooth transition into new crop growing environments brought about by climate change. It also appears that policy makers have turned a deaf ear on the issues of negative externalities brought about by the heavy use of fertilizers and agrochemicals, associated with the Green Revolution. Interestingly, it has been well documented that the policy of subsidies on fertilizers and agrochemicals has worked much more favorably to the advantage of the rich than the small and marginal farmers.

The Green Revolution's genetically uniform crops have also proved more susceptible to pests and diseases (Holt-Gimenez, 2006 [42]). To protect these crops, ample amounts of increasingly powerful and selective pesticides

are released into the biosphere at considerable environmental and human costs (Thomptson et al., 2007 [41]). Also totally ignored is the central role of local communities, their traditional seed systems, and rich indigenous knowledge (Subedi et al., 2003 [61]), despite increased international recognition of their crucial importance. Rather than building on these foundations and on the tremendous treasure trove of biological diversity that is available in villages, the technological packages associated with the Green Revolution have replaced them with an increasingly narrow base of HYVs. When locally adapted traditional cultivars and local knowledge are lost, farmers will face hard time adapting to future climate variability with the help of genetically uniform HYVs. While it is important to capitalize on the tools of science and technology in improving agricultural productivity, it is also important to harness the accumulated experience and tacit knowledge imbedded in the practice of agriculture across various part of the world and adapted over generations in the local contexts.

3.2. Agro-Biodiversity, Resiliency, Livelihoods, and Food Security

Agrobiodiversity is the central tenet of smallholder agriculturalists across the world. It has been argued that agro-biodiversity contributes to ecological stability, system resiliency, and overall productivity (Sthapit et al., 2006 [62]). Agrobiodiversity plays an important role in the provisioning of ecosystem services, i.e., production of foods and fibers. In a wider context, agrobiodiversity also serves important functions enhancing the resource base upon which agriculture depends (Jarvis et al., 2008 [63]). It has also been argued that if agrobiodiversity deteriorates, the farming system becomes more vulnerable to climatic perturbation, insects, pests, and diseases (Harlan, 1975 [64]). Unfortunately, the Green Revolution has reduced agrobiodiversity to two levels. First, it has replaced traditional cropping patterns encompassing combinations of cereals (e.g. rice, wheat, millet, maize), leguminous (e.g. lentil, peas, chickpea) and oilseed (e.g. mustard, linseed) crops, to monoculture of rice and wheat. Second, the introduction of rice and wheat HYVs came from a very narrow and alien genetic base in which the food supply of millions of smallholder agriculturists are precariously perched (Harlan, 1975 [64]; Brush, 1991 [65]). Reduced genetic base in HYVs has increased the chances of new insects, pests and disease. Even where HYVs are bred for disease resistance, breakdown to diseases and insects is occurring rapidly and demanding continuous replacement (Alteiri et al., 1984 [66]; Letourneau et al., 2011 [67]). For example, when the PR-106 rice variety was introduced in India's state of Punjab in 1976, it was considered resistant to white-backed plant hopper and stem rot. It has since become susceptible to both the diseases, in addition to succumbing to multiple other insects and pests (Jishnu et al., 2010 [47]). The loss of genetic diversity is thus a "common threat to the sustainable use of plant genetic resources to meet the present needs and aspiration of the future generation" (Chang, 1985 [68]).

The Green Revolution has drifted mankind to gradual genetic erosion with a consequence on limited opportunities to develop new varieties that would be adaptive to a changing climate. In the last 50 years, about 75% of the genetic diversity of agricultural crops worldwide has been lost from their major food crops (International Assessment of Agricultural Knowledge, Science and Technology for Development [IAASTD], 2008 [69]), and the rate of erosion continues at 1-2% per annum (FAO, 1996 [70]). Today, of the estimated 300,000 species of plants, about 7,000 are cultivated or collected for food, and 12 species of plants currently supply 80% of the world's food (FAO, 1996 [70]; Johnson, 2008 [71]), and just 3 – wheat, maize, and rice – supply more than half of the food supply, a precarious state of affair, in terms of reduced genetic diversity. A wholesale loss of plant genetic resources, which is known as "genetic wipeout" (Harlan, 1975 [64]; Wilkes, 1993 [72]) continues to occur throughout the world. It is estimated that, given the current trend, up to 60,000 (about 25% of the world's total) plant species will be lost by the year 2025 (International Centre for Agricultural Research in the Dry Areas [ICARDA], 1996 [73]). In India, prior to the Green Revolution, some 30,000 landraces of rice were grown, while presently the bulk of the production comes from less than 50 modern varieties (Pulchnett et al., 1987; Hardon, 1997 [74]). In China, likewise, of nearly 10,000 wheat varieties grown in 1894, only around 1,000 remained by the 1970s. In the United States, over 90% of the local cultivars of cabbages, maize, and peas grown in the last century have been lost from the system (FAO, 1996 [70]).

Should the locally adapted varieties be lost and the genetically uniform varieties be weakened by unusual episodes of epidemic, then it is likely that the latter will become more susceptible to new insect attacks and disease that are to be expected in the face of changing climate (K. Ammann, 2009 [75]). As a consequence, food production will be substantially impacted. To cope with such crisis, people will explore new livelihood strategies, which may not be ecologically resilient and environmentally friendly. Genetic diversity is essential to avoid vulnerability to pests and diseases that are expected to be more common in the future (Kesavan and Swaminathan, 2006 [45]). By ensuring the promotion and development of location specific agricultural practices, science and technology can play a pivotal role in maintaining genetic diversity. We suggest that the future agricultural development systems should begin with local communities who can integrate the principles of ecology to technology development and dissemination. As pressure on land and water continue to grow, there will be the need for productive genotypes of crops that can perform well under conditions of marginal environments such as dryland and poor soil. Some of the underutilized crops such as millets, barley, buckwheat, and others, for example, are not only nutritious but are also capable of performing well under fragile and climatically marginal conditions (Kesavan and Swaminathan, 2006 [9]; Swaminathan, 2010 [45]). Such crops need to be part of the calculus when planning the

future of agricultural development.

3.3. Water Scarcity: Competition, Crisis, and Conflict

Water demand in most countries in South Asia is gradually rising because of the increasing demand from population, irrigated agriculture, and growth in industrial sector (Mirza and Ahmad, 2005 [76]). At the same time, water availability in most countries of South Asia is gradually decreasing. For example, per capita water availability in Pakistan has decreased from 5,650 m^3 in 1951 to 1,000 m^3 in 2001-02 accompanied by sharp deterioration in quality of water (Kahlown et al., 2003 [77]). In India, per capita water availability has fallen to 1,869 m^3 from 4,000 m^3 2 decades ago, and it could dip below 1,000 m^3 in the next 20 years (Gupta and Despande, 2004 [78]). Simultaneously, the inefficient management of water resources has led to the problem of water quality deterioration posing new challenges in water management (Molden and de Fraiture, 2004 [79]). Though most South Asian countries are blessed with valuable ground water resources, in the recent years, several countries in the region are mining their aquifer faster than its recharge. The aquifer depletion could reduce South Asia's grain harvest significantly in the future (Kataki et al., 2001 [80]).

Agriculture accounts for about 70% of water use worldwide, and the total consumption made by this sector is only increasing (Molden, 2007 [81]). According to the MA (2005 [12]), between 1900 and 2000, water use for agriculture has grown 5 times with the consequences on ecosystems and human livelihoods. It is estimated that 0.5 m^3 and 4 m^3 of water is required, respectively, to produce vegetable food and animal products equivalent to 1,000 kcal (Rockstrom et al., 2007 [82]). It is reported that the rates of water extraction for irrigation are exceeding the rates of replenishment in many places, including South Asia. For example, heavily subsidized tube wells in India bring approximately 200 km^3 of water to the surface every year. Over the last decades, tube wells have pumped many water tables dry, forcing vast areas to return to the traditional dryland farming or to give up farming altogether. According to India's hydrologists, nearly a fifth of the subcontinent is withdrawing more water than is being replaced by rain. In Punjab, home of the Green Revolution, nearly 80% of the groundwater is now "overexploited or critical." As a result, many streams and rivers are increasingly being depleted (Rockstrom et al., 2007 [82]). This draw down may be irreversible. Because most of these grains are exported, the hydrological result of the Green Revolution packages is the sacrifice of India's ancient aquifers to the voracity of the international grain trade [83], a situation that is sure to become more critical given the predicted climate change, especially warmer temperatures.

The Green Revolution that relies on the lavish use of water must be met against a backdrop of rising global temperatures and changing patterns of precipitation along with competing demand for water in urban areas. To date, in India, for example, a sizable amount of resources is poured into research and development of rice genotype, with heavy focus on hybrid seeds. But the question is whether it is the right option for millions of smallholder farmers, who have been practicing agriculture for generations, and who have successfully developed richly verdant tapestry of rice farming systems. Since every kilogram of rice requires 4,000-5,000 L of water (Jishnu et al., 2010 [47]), the solution to increasing rice productivity may hinge upon the ability of farmers and their supporting institutions to find technologies that are robust and sustainable. We need a system of agriculture that increases food productivity in perpetuity without associated ecological harm (Kesavan and Swaminathan, 2006 [45]; Ammann, 2008 [84]). The need for emulating the aspects of ecological agriculture while designing the future food production systems has therefore, become very important.

3.4. New Multiple Challenges and Greater Number of Obstacles

Smallholder farmers currently face substantially different challenges compared to the Green Revolution producers, who achieved sustained gains in agriculture productivity during the early decades of its application. While global food production increased by well over 130% since the 1960s, the productivity of major cereal crops seemed to be reaching biological limits (at least in some regions), despite increasing use of inputs, (Tilman et al., 2001 [85]). Among others, this low level of performance has been exacerbated by unpredictable climate in the recent years, lack of investments in agricultural research, and increasing competition for water. Food production would be likely to decline in the developing countries, whereas the more developed countries may actually benefit from global warming, at least in the early stages (Gitay et al., 2001 [83]). Climate change could adversely impact food security through reduced crop yields, geographical shifts in optimum crop-growing conditions, reduced water resources for agriculture and human consumption, loss of cropping land and yields through floods, droughts, and sea-level rise (Lobell et al., 2008 [86]).

In India, for three consecutive decades, rainfall departures are found to be above and below the long-time averages (Kothyari and Singh, 1996 [87]), with recent decades exhibiting an increase in extreme rainfall events over northwest India, notably during the summer monsoon (Singh and Sontakke, 2002 [88]). Lal et al. (1995 [89]) suggested that the surface air temperature over the Indian subcontinent (area averaged for land regions only) is likely to rise from 1.0°C (during the monsoon) to 2.0°C (during the winter), by the middle of the next century. The rise in surface temperature could be quite significant across the semiarid regions of northwest India. Populations in arid or semi-arid areas of South Asia are the most vulnerable because of their heavy dependence on rainfall. Climate change is increasing pressure on an already fragile natural resource base in the complex and often risk-prone crop production environment that is the mainstay of smallholder farmers (Erickson, 2006 [90]). Thus, any

change in climate will have severe consequences in food production.

Two reasons underlie the differential impacts that climate change is expected to have in agricultural productivity between developed and developing countries. The first is the physical factor. In developed countries, most of which are located within the higher latitudes (temperate zone), agriculture would benefit from the longer growing seasons that would accompany a warmer climate. However, in developing countries situated in the lower latitudes (tropics), most crops have already attained their climatic threshold, and therefore, crop yields are likely to be adversely affected even with a small change in climate. The second reason is the socioeconomic factor. Compared with developed countries, developing countries have lesser economic resources to help farmers adjust to the climate change. The technical capabilities and institutional structures in developing nations that are needed to cushion the adverse effects of climate change are comparatively less developed or may even be non-existent. These comparative disadvantages, whether physical or socioeconomic, underscore the greater vulnerability of developing countries to climate change, and its subsequent effect on food security.

The vulnerability of agriculture to climate change in South Asia and other developing countries of the world also comes from factors associated with socioeconomic, political, and technological conditions limiting their ability to adapt to change (Adger et al., 2003 [19]; Easterling et al., 2007 [91]). For example, ongoing stresses related to demographic change, human immunodeficiency virus/acquired immune deficiency syndrome (HIV/AIDS), land degradation, economic globalization, property rights, and conflicts increases the exposure to greater food insecurity. Morton (2007 [92]) lists a series of stressors affecting the livelihood of agrarian populations. Some of the stressors are very likely to worsen the effects of climate change. For example, population growth not only demands additional food from the land, but in rural areas it drives land degradation and fragmentation (Blaikie and Brookfield, 1987 [93]). A change in resource endowments due to the effects of climate change aggravates resource degradation and fragmentation effects. Likewise, environmental degradation caused by population growth and ill-defined property rights may hinder the adaptive capacity of smallholder farmers in rural areas.

Aside from climate change, smallholder farmers are currently experiencing a number of interlocking stressors emanating from global economic change (Thompson et al., 2007 [41]; Easterling et al., 2007). Rising energy prices are driving massive investment in biofuels, increasing the volatility of food prices to the poor and marginal sector of the society (von Braun, 2010 [15]). At the same time they also possess strong adaptive capacity such as improved efficiency in the use of household labor (Lipton, 2004 [94]), diversification of livelihood (Ellis, 2000 [95]), and management of indigenous knowledge that collectively make them more resilient. The combination of stressors and resilience factors equip them to cope with and adapt to unforeseen events, but climate change also poses novel risks often outside the range of farming experience such as impacts due to extended and frequent droughts, intensive rainfall, and heat waves (Adger et al., 2007 [96]).

3.5. Adapting to Climate Change Requires Different Levels of Thinking and Planning

Until recently, adaptation – a process by which societies address the consequences of climate change – was a taboo subject in climate change discussions, where it was viewed as undermining efforts to reduce GHG emissions (Pielke et al., 2007 [97]). However, the realization that, even in the best case scenarios, emissions reduction can have little effect on social vulnerability to climate impacts over the next several decades has prompted the resurgence of interest in adaptation to climate change. Indeed, adaptation has been an ongoing and dynamic process, whereby societies have adjusted to change and variability of climatic and non-climatic factors throughout history, albeit with variable success (Adger et al., 2003 [91]; Klein et al., 2007 [98]; Jodha, 1978 [99]; Diamond, 2005 [100]). Over time, societies have used technological innovations and institutional arrangements to adapt to climatic stresses. Yet, the capacity to adapt to climate change, which is typically based on local knowledge, remains poorly understood by researchers and decision makers alike. Useable knowledge about adaptive capacity holds particular urgency as it relates to the vulnerability/resilience of livelihoods and agroecological systems in developing countries, and by extension to the growing concern of the global food crisis.

Past emissions of greenhouse gases have already committed the globe to further warming of around 0.1°C per decade for several decades (IPCC, 2007 [20]), and hence, some level of impacts and necessary adaptation responses are already unavoidable. Agriculture, including land use change following deforestation, contributes to about 30% of the total GHG emissions (World Bank, 2007; IAASTD, 2008). The emission of the major GHGs is continuing to increase rapidly (IAASTD, 2008 [69]), while the resultant changes in global climate are already on the high end as those implied by the scenarios considered by the IPCC (Howden et al., 2007 [26]). Evidence also shows that climate change is already underway, and its impacts are happening faster than previously considered likely (Lal, 2011 [28]). Extreme climate events are likely to slash yields for rice, wheat, maize, and other primary food crops. For instance, Asian rice yields are expected to decrease dramatically due to higher nighttime temperatures. With warmer conditions, photosynthesis slows or ceases, pollination is prevented, and dehydration sets in. As mentioned earlier, a study by IRRI shows rice yields declining by 10% for every degree Celsius increase in nighttime temperatures. South Asia's prime wheat-growing land, the vast Indo-Gangetic plain that produces about 15% of the world's wheat crop will shrink by more than 50% by 2050 due to warmer, drier weather, and the diminished yields and

loss will potentially place at least 200 million people at a greater risk of hunger and starvation.

Approximately 95% of the rice in China and Korea and 70% of the rice in India and the Philippines are considered modern varieties; there is no question that the rate of growth of food output per capita has exceeded the population growth rates in these countries since 1950 because of the productivity gains of the Green Revolution (Conway and Toenniessen, 1999 [101]). However, agriculture today, whether small-scale or large-scale, faces an increasing array of challenges. This may be in the form of new pests and diseases, soil nutrient depletion, water scarcities, or unpredictable climatic patterns. They affect agricultural systems making them less robust and resilient to cope with change (Scoones et al., 2007 [60]). Climate variability and change present particular challenges, especially in drier, rainfed cropping systems. Thus, it is the dynamic interactions between nature and society (e.g., climatic, agronomic, and disease dynamics) that need to be taken seriously in thinking about future socio-technical trajectories.

4. Conclusion

Within the normalcy of science and technology, the Green Revolution was one of the greatest technological advancements of the last century. For all its innovativeness and achievement, however, it failed to recognize the relevance of tacit knowledge, agrobiodiversity, diversity of agricultural production systems, and meaning of agriculture in smallholder communities. Most importantly it assumed "stationarity" in climatic resources. Its immaculate faith in the power of modern science and technology, and its belief that traditional knowledge was inadequate to create the scales and the levels of productivity required for farmers of developing countries has come face-to-face with a new civic consciousness. Along with creating the vocabularies of risk and vulnerability to the Green Revolution, the discussion about the need to adapt to climate change have given the resurgence of Vavilovian debates on diversity and tacit knowledge; what was once an embarrassment and folklore now enters into the debate of science and technology (Funtowicz and Ravetz, 1993 [102]). But, can the same science and technology that the world celebrated as victory in eliminating hunger enable us to deal with the new and emerging problems more efficiently and sustainably? And, can the Green Revolution technologies match the world's growing food need while maintaining diversity and resiliency of the agricultural systems in the coming decades and for a longer term?

There is a sharp dichotomy in perception between farmers who are searching for sustainable livelihoods through robust agricultural systems and the policy makers who continue to renew interest in the Green Revolution for boosting crop yield (Jishnu and Pallavi, 2010 [47]). For example, in the Mandya district of Karnataka, rice farmers are gradually switching to traditional rice varieties, which had disappeared after the establishment of an irrigation canal in the area. Not surprisingly, the rice productivity went down a bit with this switch (2.7-3 t/ha; the national average is 3.37 t/ha), but the local varieties, which are also revered for their drought-tolerance and aromatic taste, are doing well during the period of uncertain climate and fetching better market price (Jishnu et al., 2010 [47]). Gauchan et al. (2003 [103]) also demonstrate that some of the high quality (e.g., fine grain and aromatic taste) local varieties provided much better price incentives to the farmers than the high-yielding modern varieties. Increasingly, scholars and practitioners point out that the significant strategy to enhance agricultural productivity in the future is to improve upon the diverse set of agricultural practices and knowledge, which evolved due to local ecological requirements and cultural norms of the region in question (Brush 1991 [65]), and that the agricultural practices promoted during the Green Revolution era are in crises and cannot make a smooth transition to address future challenges.

Agricultural systems in the 21st century require policies and actions that not only contribute to social objectives like food production but also to achieve continually modified and enriched understandings of the evolving ecological, economic, social, and political conditions, and provide flexibility for adapting to surprises (Thompson et al., 2007 [41]). We argue that science and technological innovation that led to the Green Revolution in the 1960s have failed to provide sustainable outcomes, especially for a large number of smallholder farmers in developing countries. By contrast, social and institutional mechanisms behind the Green Revolution have not attempted to understand the dynamics of farming systems of smallholder farmers, and to support their agricultural systems so that they become more resilient and robust in order to cope with interannual disturbances and irregularities associated with climate change.

Based on our review of the outcomes of the Green Revolution and the continuing need for food security in the changing context, we propose the following 3 considerations:

1 It is important to defend the gains that the society has already made in food security. This may involve integrating practices of both modern and traditional agricultural systems in the science and technology policy of the 21st century. This also involves the promotion of policies that emphasized the sustainability of available natural resources and holistic approach to agricultural development as opposed to the commodity approach of the Green Revolution.

2 We must extend our technological prowess in agriculture for the benefit of small and marginal farmers around the world, whose crop-growing environment is more vulnerable to the vagaries of climate. Enabling these smallholder farmers with location-specific technology, services, and policies will contain the problems of food security at its origin.

3 Science and technology should make new gains, es-

pecially in rainfed and dryland agricultural systems, which constitute more than 60% of the farm area in the developing world. A policy that emphasizes the knowledge base of the farmers, promotes genetic diversity of crop, and agronomic practices that are resilient and socially just.

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- N. Chhetri, "Water demand management: assessing impacts of climate and other changes on water usage in Central Arizona," Journal of Water and Climate, Vol.2, No.4, pp. 288-312, 2011.
- N. Chhetri, "Climate sensitive measure of agricultural intensity: Case of Nepal," Applied Geography, Vol.31, No.2, pp. 808-819, 2011.
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