ELSEVIER

Research Policy 32 (2003) 971–990

research policy

www.elsevier.com/locate/econbase

Mapping technological trajectories of the Green Revolution and the Gene Revolution from modernization to globalization

Govindan Parayil*

Information and Communications Management Programme, Faculty of Arts and Social Sciences, AS3 #04-16, National University of Singapore, Singapore 117570, Singapore

Received 22 August 2001; accepted 1 August 2002

Abstract

The dynamics of technology development along the technological trajectories of the Green Revolution and the Gene Revolution could be explicated by the social morphologies of modernization and globalization. The Green Revolution was shaped by the exigencies of modernization, while the Gene Revolution is being shaped by the imperatives of neo-liberal economic globalization. Innovation, development, and diffusion of technologies followed different trajectories in these two realms because of being part of different innovation systems. Considerations of private gain and profit in the form of high returns to shareholders of agro-biotech corporations of global reach, largely, determine the dynamics of technological innovation in the Gene Revolution. Technology transfer and local adaptive work in the Green Revolution was carried out in the international public domain with the objective of developing research capacity in post-colonial Third World agriculture to increase food production to avert hunger-led political insurrection during the Cold War. Differentiating these two trajectories is important not only due to the normative implications inherent in comparing the impacts of these two "revolutions", but also due to the important lessons we learn about how different contexts of innovation in the same technology cluster could evolve into contrasting research policy regimes.

Keywords: Technological trajectory; Innovation; Biotechnology; Green revolution; Gene revolution; Modernization; Globalization

1. Introduction

The objective of this paper is to compare the "Green Revolution" and the "Gene Revolution"—two different technological trajectories of modern biotechnology—at a macro level. Many analysts tend to assume or confuse that the Gene Revolution is a continuation of the Green Revolution by other means, such as by infusing advanced genetic technology into agricultural production. Conway (1998) exhorts the urgency of incorporating advances in genetic technology to make the Green Revolution environmentally more sustainable. He sees the recent advances in molecular genetics in agricultural biotechnology as a continuation of the innovation process in the Green Revolution. "The Green Revolution strikes gold" is Guerinot's (2000) characterization of the invention of the so-called "Golden Rice." Guerinot makes this claim without realizing that the invention of the "Golden Rice" was not part of the Green Revolution, which was essentially an international technology transfer/assistance programme in the public domain to improve agricultural productivity of Third World farmers. The so-called "Golden Rice" is owned by Syngenta, world's largest biotech multinational,

* Tel.: +65-6874-6320; fax: +65-6779-4911.
E-mail address: icmgp@nus.edu.sg (G. Parayil).

0048-7333/02/$ – see front matter © 2002 Elsevier Science B.V. All rights reserved.
PII: S0048-7333(02)00106-3

whose mission is not to feed β-carotene enriched rice to vitamin A deficient children in the developing world, but to enhance the profit of its shareholders through this biotech innovation. In a critical commentary on agro-biotech corporations that promote GM crops for profits without any regard to their potential harms, the Thistle (2001) argues that the recent biotech revolution is "a natural outgrowth of the Green Revolution" without paying attention to the different history and politics of these two socio-technological changes. Serageldin (1999a) also sees the difference between the Green Revolution and the Gene Revolution in terms of only the scientific advance of the latter over the former. He argues that the Gene Revolution should be turned into a "doubly green revolution" such that "increased productivity and natural resource management are in balance."

The major thrust of this paper, therefore, is to show that the Green Revolution and the Gene Revolution are entirely different socio-technological systems in that these two "revolutions" involved different technological trajectories that were moulded under different social, political, and economic contexts. I will show that the contexts of these two revolutions have been progressively constructed. While the Green Revolution ended in the 1980s, the Gene Revolution took off in the 1990s under a different socio-technological regime and it was not a technological reincarnation of the Green Revolution under a different name. Differentiating these two trajectories is important not only due to the normative implications inherent in comparing the impacts of these two "revolutions", but also due to the important lessons we learn about how different contexts of innovation in the same technology cluster could evolve into contrasting research policy regimes.

The differential dynamics of these two trajectories are apparent from the fact that despite efforts to revive the Green Revolution under changed international political economic contexts during the late 1980s and 1990s, the crucial international technology transfer and research capacity development regime collapsed due to the transformation and reconfiguration of the milieu of biotech innovation in the wake of globalization. Efforts to revive the Green Revolution under the rubric of a "Doubly Green Revolution" (Conway, 1998) did not take off due to privatization of the research infrastructure and technology transfer regime after the end of the Cold War, and also due to the influence of neo-liberal doctrines curtailing international aid and capital and technology flow gravitating to new players on the international arena.

In this paper, we will look at the processual dynamics of technological change in biotechnology to trace its trajectories since the mid-1950s. Biotechnologies of various forms and styles have been part of almost all societies and civilizations since antiquity. By biotechnology I mean all human endeavours to alter living things to produce food, fodder, and fiber. More specifically, it means "[A]ny technological application that uses biological systems, living organisms, or derivatives thereof, to make or modify products or processes for specific purposes".[1] Conventional methods of tissue culture, cell fusion, selection and cross-breeding of plants involved in the Green Revolution to the recombinant DNA and genome shotgun sequencing techniques employed in the Gene Revolution would fall under the spectrum of modern biotechnology. Biotechnology is conceptualized in an expansive sense, as a package of artifacts, practices, and knowledge, to produce agricultural crops. The temporal focus will be from around the middle of the 20th century to the present, while the spatial focus will be on the Third World as well as Western industrialized nations. We will look at what global political economy and societal factors shaped the Green Revolution (1950–1980) and how a different set of such factors are shaping the Gene Revolution (1980 to the present) and their policy implications.

2. Technological trajectories of biotechnology

The clustering of innovations and the dynamics of technology development in modern biotechnology shows a clear pattern of technological trajectories. Nelson and Winter (1977) and Dosi (1982) posited the concept of technological trajectory as the path blazed by the normal developmental dynamics of a technology. Technological trajectory is defined by a technological paradigm that emerges from specific selection environment as the solution to the particular

[1] This is the definition given to biotechnology in the 1992 Rio Convention on Biological Diversity or CBD. Quoted in Adler (2000, p. 175).

cluster of technological problems in question (Dosi, 1982). Dosi showed how the trajectory is circumscribed by such factors as raw materials, scientific laws, industrial conflicts, functional constraints, market forces, laws and regulations. Technological trajectories and paradigms are useful heuristics to explain ex-post facto the developmental dynamics of new technologies within neo-Schumpeterian evolutionary framework of firm-based innovation. In this scheme, the process of technological innovation remains an uncertain activity of selection, "niche" finding, adaptation and other learning and problem solving activities within the milieu of firms and associated actors.[2] Devoid of a clear account of the extant political, economic, historical, and cultural factors in shaping the innovation process, technology dynamics remains a partially useful concept, but fails to provide a clear and comprehensive account of technological change.

In order to present a comprehensive account of the processes and factors that shape technology, one needs to discard all seemingly internalist–externalist or content–context dichotomy and, instead, should follow a contextualist approach to unpack the complexity of how technologies evolve as a contingent and self-organizing process.[3] The self-organizing notion is within the ambit of evolutionary change of technological systems where the selection mechanism is shaped by specific societal forces. The agency question falls within the confines of the society–technology dialectic, and mutual production and reproduction becomes a self-organizing process that is non-deterministic. The implication is that technological change is not an autonomous process, but rather the shaping of technology involves diverse societal agents with differential power relationships derived from their strategic positions in the social matrix. Thus the heuristic of contextualism is to recognize both the contingent and emergent nature of technology development, such that the particular political, economic, historical and epistemic factors shaping technology could be discerned through careful analysis (Staudenmaier, 1985; Latour, 1987; Bijker and Law, 1992; Callon, 1987; Pinch, 1996; Misa, 1992).[4] In order to explicate the complexity of technological change, a useful approach is to look at the social shaping of technology in a contextualist spectrum of macro-level processes within the epistemic context of technology as knowledge.[5] Contextualism enjoins both constructivist and evolutionary modes of theorizing on technological change by being reflexive of the agential milieu of the actor-network mobilized along these two technological trajectories.[6]

We could explicate the dynamics of technology development in modern agro-biotech innovation systems by following the contextualist frameworks of modernization and globalization. In this article, I argue that the technological trajectory of the Green Revolution was shaped by the exigencies of modernization in post-colonial societies, while the technological trajectory of the Gene Revolution is being shaped by the imperatives of neo-liberal economic globalization. It will be shown that in addition to different set of external factors acting as focusing devices for the selection environment, technological trajectories in these two realms are also shaped by various techno-scientific factors and micro-level processes. It is important to note at the outset that these two major socio-technological changes are very different in nature—the Green Revolution refers to

[2] The fact that uncertainty always pervades technological innovation is well known (Rosenberg, 1998). However, it is possible to identify and analyze the factors behind many uncertainties and possibly steer the course of technological change, to a large extent, through appropriate technology policy measures (Rosenberg, 1998; Parayil, 1999).

[3] As Latour (1987, 1988) has clearly shown, any claim of a divide between internal (knowledge) and external (society) of techno-science is a non-starter in conceptualizing technological change. Technology and society are inextricably bound up in a "seamless web" (Hughes, 1986) of human and non-human actors involved in mutual shaping and reshaping of technology and society (Callon, 1987).

[4] If we substitute the word "science" for "technology" in Kuhn's (1970) classic opening sentence in *The structure of scientific revolutions*, one could find the historicity of technology's shaping similar to that of science's.

[5] Intellectual roots of this argument could be traced to the systems model of Hughes (1983, 1987), the actor-network model of Latour (1987), Callon (1987), and Law (1987), social construction of technology (SCOT) model of Pinch and Bijker (1987), contextualist spectrum of Merrit Roe Smith and Reber (1989), and technology as knowledge argument of Layton (1974, 1989), Vincenti (1984, 1990), and Rosenberg and Vincenti (1978). Thomas Misa's (1992) argument that a meso-level analysis captures the complexity of technological change is also a precursor to the contextualism argument presented here.

[6] The contingent and emergent nature of technology dynamics is eminently captured in most of the pioneering works cited above.

a major project of international technology transfer in the post-colonial era, while the Gene Revolution refers to a process of knowledge intensive innovation which takes place in the industrialized world whose impact will have tremendous implications on agricultural technology and food safety and security of both the developed and developing worlds.

The Green Revolution is very much a product of technological innovation in the international public domain where Western and Third World governments, public supported non-profit national and international agricultural research institutions, universities, multilateral aid agencies, and Western charitable organizations collectively worked together to increase agricultural productivity. The technology transfer and local adaptive work was carried out by public agencies. The objective was to transfer and develop knowledge and research capacity in agricultural innovation and transfer new agriculture practices and necessary technological inputs to farmers in strategically important Third World countries from Western countries during the Cold War.

Unlike the Green Revolution, the Gene Revolution is being shaped by dominant forces in the international private domain where the technological innovation process is determined, largely, by private capital and its quest for profit, market share and shareholder value. The technological trajectory is being shaped by the tension between the public and private domains because of the exigencies of globalization. Most of the knowledge that is being mobilized and utilized by the private agro-biotech corporations to develop proprietary technologies comes from local and global public knowledge domains (government, academe, and global/local intellectual commons). The trend is to privatize the means and sources of knowledge production and to deploy strategies to enclose knowledge commons through intellectual property right regimes.[7]

Both the Green Revolution and the Gene Revolution are different versions of global and national innovation systems in agricultural biotechnology. We could reconfigure several macro models of innovation to capture the dynamics of innovation in these two realms of biotechnology.[8] However, my objective is not to demonstrate the effectiveness of these models to capture the dynamics of innovation in biotechnology. Without going through an exhaustive analysis of the applicability of any of these models, it could be argued that the trilateral approach of looking only at government, industry, and academe acting as the backbones of the innovation process needs to be bolstered by expanding the agential milieu to include other significant actors (such as NGOs) involved in this complex process.[9] But before proceeding further let us look at the technological change in modern agriculture in its two phases mentioned earlier.

3. The Green Revolution and its dynamics

3.1. *What is the Green Revolution?*

The beginning of the so-called "Green Revolution" could be traced to the year 1954 when Norman Borlaug invented strains of "miracle" dwarf wheat in Mexico at what is now known as the International Maize and Wheat Improvement Center or CIMMYT. The precursors to the Green Revolution could be traced to the spectacular increase in productivity of hybrid maize (corn) experienced by US farmers in the 1930s and 1940s and to the Rockefeller Foundation-led effort in the 1940s to increase the productivity of wheat and maize in Mexico (Kloppenburg, 1988). Also the agricultural research system that evolved during the post-colonial period in many Third World countries that helped to create the Green Revolution had benefited from the colonial agricultural research system

[7] For an excellent exposition of the concept of intellectual commons and a rationale for public regulation of intellectual commons to prevent its ruin through uncontrolled exploitation, see Dawson (1998).

[8] Leading exponents of these models of innovation are: Freeman (1987), Lundvall (1992), and Nelson (1993, 2000) on national innovation system (NIS); Gibbons et al. (1994) on "Mode 2"; Saxenian (1994, 2000) and Acs et al. (2000) on regional economies and innovation networks; and, Etzkowitz and Leydesdorff (1997, 2000) and Leydesdorff (2000) on the "Triple Helix" of university–industry–government relations. In the case of agricultural innovation, many scholars use the term "National Agricultural Innovation System" or NAIS (Hall et al., 2000).

[9] However, as will be argued later, a government–university–industry interactive model is appropriate, but with limitations (as discussed in the concluding section), for capturing the innovation process in biotechnology. We could argue that the Green Revolution had followed some aspect of the NIS or NAIS mode, while the Gene Revolution may be following the Triple Helix mode.

established by imperial governments to support the production of commercial export crops such as cotton, rubber, tea, coffee and spices (Hall et al., 2000).

The term “Green Revolution” refers to the changes in agriculture technology and mode of practice of agriculture experienced by some Third World countries, mostly in Asia and Latin America. As a result of the changes in their technological capacity and agrarian relations, these countries experienced considerable increase in the production and productivity of basic cereals like wheat and rice (Parayil, 1992, 1999; Binswanger and Ruttan, 1978).[10] It involved a set of technology policy measures and practices to force nature to be bountiful through the transfer and adaptation of simple technological fixes. In terms of the rate of change of technological change, the Green Revolution was the first major radical innovation in agriculture for several centuries since the introduction of the plough.[11] It is an instance of a relatively “successful” technology transfer, in terms of increases in per capita cereal production.[12] It presents a circumscribed way of looking at a narrowly defined technology policy objective of increasing agricultural productivity.

Generally, the Green Revolution involved the use of seeds of high-yielding varieties (HYVs), primarily of wheat and rice, and the adoption of a “modern” package of agricultural tools and practices involving chemical fertilizers, tractors, pesticides, controlled water, mechanical threshers, electric and diesel pumps, and so forth. These changes were instituted in place of the “traditional” agricultural practice involving the use of seeds whose genetic composition went back thousands of years. “Traditional” technologies also include wooden ploughs, waterwheels, and bullock carts. In the traditional mode, animals and humans provided the energy required for all agricultural activities. Finally, traditional agriculture is dependent on the vagaries of natural irrigation provided by rains. While the traditional mode involved subsistence production, the modern practice was based on market production. More details of the technical and institutional aspects of the Green Revolution will be presented with occasional reference to India’s Green Revolution to flesh out the details of the technology transfer, innovation, and diffusion of this technological event in a concrete setting. India is considered an example of the success of the Green Revolution that made the country self sufficient in food grain production, and even an exporter of grains.

Subsistence farming is often characterized by an “exclusion effect,”[13] which is a tendency on the part of peasant farmers to resist modernization and technological innovation, specifically, to resist radical innovations. This tendency to maintain status quo, and consequently not to undertake innovations, culminated in depressed agricultural productivity, which in turn forced many Third World governments to formulate and implement a new agricultural policy to break out of the stasis in production. The situation was compounded by droughts that culminated in a near-famine situation in the 1960s in many Asian countries. The prevailing policy was for the agricultural sector to fend for itself, and it was expected to provide the surplus to sustain the emerging industrial sector. The decline in food production due to negligence and the lack of cooperation from nature (droughts) forced the governments to depend on imported food to avert hunger and famines. This frightening food situation forced Third World governments, under heavy external pressure from aid donors and the World Bank, to introduce a new agricultural policy for increasing food production (details of the external political economy factors to be discussed anon).

The agricultural policy was aimed at increasing land productivity by introducing a technological solution

[10] The term itself was coined by William Gaud in a speech entitled “The Green Revolution: Accomplishments and Apprehensions” given at the meeting of the Society for International Development in 1968. For more details on this naming episode, see Dalrymple (1979) and Binswanger and Ruttan (1978).

[11] This claim must be qualified because agriculture involved numerous innovations through the ages, such as the introduction of water wheels, selective breeding, crop rotation and so on. However, these changes occurred gradually, as opposed to the innovations involved in the Green Revolution and the Gene Revolution, which occurred in a short time span of half century in human history.

[12] In countries such as India, Pakistan, Philippines, Mexico, Turkey and Indonesia, rice and wheat yields more than doubled in two decades. See Gordon Conway (1998) for productivity statistics, especially Chapter 7.

[13] Dosi (1982) defines “exclusion effect” in a different context involving technological paradigms as a tendency on the part of engineers and R&D personnel to be “blind” to other notional possibilities of technological innovation besides the one they “select” as the solution to a given technological problem.

in the form of the Green Revolution package of technology. This was partly indigenously developed, but mostly developed and transferred from the West to India and other countries. There was no intention of introducing land reforms or changing agrarian relations such as introducing serious land reforms. The policy objective was to target medium to large farmers who were encouraged to adopt the new agricultural practices. The Green Revolution has made countries like India self-sufficient in food grains *production* even though its spread was uneven because of inequalities in land tenure, education, infrastructural facilities and so on. The Green Revolution also caused enormous environmental problems, an important topic beyond this paper.[14] The Green Revolution may be characterized as the new technological paradigm that replaced the old paradigm characterized by subsistence farming.

Succinctly put, the technological change in agriculture may be seen as the transformation of the newly derived knowledge in agricultural technology, both local and foreign, into food. The high-yielding varieties (HYVs) of rice suited to tropical conditions in Southeast and South Asia were developed in the 1960s at the International Rice Research Institute (IRRI) in Manila. The earlier varieties developed at the IRRI were based on genetic materials (germplasm) drawn from China, Taiwan, and Indonesia (Binswanger and Ruttan, 1978). These high yielding rice varieties were extensively and successfully introduced in several Third World countries in the 1960s. Semi-dwarf wheat originated in Japan in the late 19th century, and the two most important varieties used for international breeding programmes were Akakomugi and Daruma (Dalrymple, 1988). The Japanese crossed Daruma with several American varieties. The most productive variety that arose from these experiments was known as Norin 10. Norin 10 was introduced into the US in 1946 and was crossed with several native varieties by the US Department of Agriculture scientists (Dalrymple, 1986). In 1948, scientists in Washington State crossed Norin 10 with Brevor, a native variety. In 1954, the Norin–Brevor cross was taken to Mexico where Norman Borlaug and his colleagues developed several varieties of the HYVs of wheat seeds that were later transferred to India and other Third World countries (Parayil, 1992).

A reconstruction of the history of the Green Revolution shows that four protagonists played crucial roles in its implementation. They are the local and national governments of recipient Third World countries, multilateral and bilateral donor agencies, international agricultural research institutions, as well as the farmers and peasants of these countries. The institutions under the government of India, for example, which planned and coordinated the transfer and diffusion of the new technology were the Ministry of Food and Agriculture, and the Indian Council of Agricultural Research (ICAR), along with the various agricultural research institutes and agricultural universities (Parayil, 1992).

The multilateral and bilateral donor agencies were the Ford Foundation, the Rockefeller Foundation, the World Bank, and the US Agency for International Development (USAID). The two key international agricultural research institutions were the IRRI in Manila and the International Maize and Wheat Improvement Center (CIMMYT) in Mexico.[15] Several more international agricultural research institutes were established after these. In 1971, all the international agricultural research institutes were brought under the umbrella of the Consultative Group on International Agricultural Research (CGIAR).[16]

The farmers and peasants by adopting and adapting the new agricultural technology to their particular situ-

[14] It is beyond the scope of this article to give a complete account of the social, economic and environmental impact of the Green Revolution in India and other countries. The Bhopal gas explosion in India, which killed over 15,000 people during and after the aftermath, is connected to the Green Revolution. The Union Carbide factory was set up to produce synthetic pesticides. As a result of the changes in agricultural practices, hundreds of thousands of agricultural workers are injured and killed by agricultural machines, chemical fertilizers and pesticides. These "mini Bhopals" occur because the workers operate and handle these dangerous substances and tools without proper guidance and protective gears. For details of Bhopal, see Parayil (1998).

[15] The IRRI, instituted in 1960, was the joint effort of the Ford Foundation and the Rockefeller Foundation. The Philippines government provided the land for the institute. The CIMMYT, instituted in 1959, was also the joint effort of the Ford and Rockefeller Foundations, and the Mexican government provided the land.

[16] Instituted in 1971, the CGIAR is jointly sponsored and supported by the Rockefeller and Ford Foundations, the World Bank, the Food and Agricultural Organization (FAO), the United Nations Development Programme (UNDP), and recently, the United Nations Environment Programme (UNEP). See Anderson (1998) and Kloppenburg (1988) for details. IRRI and CIMMYT are two of the core research institutions under CGIAR.

ation made the Green Revolution a "successful" technology transfer event. The development and spread of the Green Revolution involved different learning processes. The establishment of agricultural universities, patterned after the land-grant universities of the US, is an important event in the history of the Green Revolution that helped to transfer "modern" agricultural knowledge from the US to several Third World countries. USAID helped with investments and logistical support to start up the land-grant type universities, the Rockefeller Foundation helped with the development of a national agricultural research system, and the Ford Foundation helped with farm extension work (Read, 1974; Lele and Goldsmith, 1989).[17]

3.2. Modernization paradigm and the Green Revolution

When the process of modernization began more than two centuries ago in Europe, a new productive relationship emerged during the ensuing Industrial Revolution as a result of the rapid proliferation of new industrial and military technologies.[18] The conflictive practices of various social actors during this period of rapid social change centered on such categories as production, consumption, power, and experience saw the rise of industrial capitalism. The rise of industrial capitalism concomitantly caused a radical shift in the modes of scientific and technological knowledge production and utilization. The transformation in the means and modes of production set off a long wave of innovation clusters around such key technologies as steam engine, electricity, chemicals, electronics, computers, and, most recently, the Internet and genetics. The coming of mass industrial society with the onset of modernization was also characterized by the proliferation of nation states as the unit of political economy. The essential features of this stage of social transformation, or what Beck (1992) calls the period of "first modernity," were controllability, certainty, security, linear progress, and convergence. Technological innovation during this stage was notable for energy intensive production, efficiency of operation, systematization, communication based on bottom–up dynamics, and vertical integration of firms and businesses.

Although most of Asia, Africa and Latin America were under colonial rule, European modernity did not make any serious impact on the social and economic structures of the colonies until after World War II when many former colonies began to gain independence and started to formulate their own development agendas. The modernization project with the infusion of new technologies implemented through different economic development models began in earnest in the former colonies during the 1950s and onwards. The common denominator of the economic development models was modern technology, the rapid infusion of which was expected to materialize through its transfer from industrialized nations. The modernization project also considered foreign aid in capital and technology as vital for achieving development. The basic assumption of modernization theory is convergence, an important ontological premise of the project that first appeared in Europe during the Enlightenment. That is, the world is on a particular Eurocentric path of economic and social change engendered by the ideals of Enlightenment; the West arrived there first, and the rest is expected to reach there eventually through a catching up process.[19]

It is axiomatic in modernization theory that Third World ("traditional") societies could be transformed through a concerted project of economic development, which can be achieved by changing the means of production (technology) and by transforming and remoulding archaic social structures that lack the wherewithal for technological innovation. It is assumed that changes in the means of production would entail a

[17] According to Read (1974), hundreds of researchers and agricultural experts from American land-grant universities went to India and other destinations to help with the establishment of agricultural universities and their research facilities. Also, thousands of Third World scientists trained in the US and UK returned to India and other nations of their origin to teach and conduct research.

[18] It is instructive to note here that before the onset of the Industrial Revolution in Europe several critical technologies and scientific ideas reached Europe before the 16th century from China, India, and Arabia. These included the magnetic compass, printing and paper making, the water mill, cast iron, iron-chain suspension bridge, piston bellows, metallurgy, the loom, the lathe, gun powder, paper, chemistry and mechanics (Needham, 1954, 1969; Hall, 1957; Adas, 1989; Law, 1987).

[19] This meta-model of modernization and the ensuing universalist narrative of progress is under attack from post-colonial and postmodern theorists of development and change. For a discursive excursus of the modernization project of "development" as an excuse for normalizing the Third World, see Escobar (1995).

change in the relations of production. Modernization can, thus, be achieved by adopting the "right" policies by the government. By formulating and implementing the "right" package of policies, the state and other agents of economic power could induce technological change, where technological change could be equated to a problem solving activity. This minimalist, though profoundly effective, model can be a useful heuristic to understand technological innovation. However, the economic development and modernization drive of Third World countries stalled and became victim to the contingencies of geo-strategic power struggle between the super powers during the Cold War.

The Green Revolution is an unlikely spill over, or perhaps spin-off, of Cold War geopolitics. It is an ironic and unexpected outcome of the campaigns by the US and its allies to check the expansion of the "Red Revolution" in the Third World. The creation of the international system of innovation that caused the increase in agricultural productivity was "closely associated with an American foreign policy that saw that food security problems, particularly in Asia, could lead to political instability and the spread of communism" (Hall et al., 2000, p. 74). The prevailing thinking was influenced by the belief that centralized scientific research institutes of international scope "could solve the generic problem of increasing the biological potential of important food crops and that this would lead to increased food production" (Hall et al., 2000, p. 72). Perkins (1997) persuasively reconstructs the political ecology of yield transformation in agriculture between 1945 and 1970 to the vagaries of geopolitics during the Cold War in which the solutions to American "national security" concerns could be found by alleviating the food deficit of strategically important Third World countries such as India, Indonesia, Philippines, and Mexico through the Green Revolution technologies. The post-colonial political and economic situation in countries of Asia, Africa, and Latin America was rather dismal. Food production was struggling to keep up with the population growth. Fighting hunger and reversing near-famine conditions in countries that still had not fallen to the "communist domino" became an important strategic policy consideration for the US and its allies like UK (Perkins, 1997).

American-led effort to transfer and locally adapt agricultural innovation converged with state-led efforts in Third World countries to modernize their economies. The inventions and innovations leading to the Green Revolution package of technologies came from the efforts of government and non-profit organizations. The public sector and private non-profit organizations played important part in the transfer and establishment of research capacity for Third World agricultural technology development. The establishment of agricultural universities, research and extension stations, irrigation facilities, seed and fertilizer distribution systems were all built by governments, in most Third World countries, to spread the Green Revolution. Markets played only a secondary role in the diffusion of the technology, while the primary role of diffusing the technology came from governmental efforts in tandem with non-profit organizations. Unlike modern biotechnology innovations, profits and private property rights were not key concerns of the developers of the technology. Political, social and, to some extent, humanitarian considerations were emphasized over proprietary social relations in the development and diffusion of the new agricultural technologies.

3.3. Dynamics of the technological trajectory in the Green Revolution

Although the exact nature of the trajectory and outcome of technological change cannot be predicted in advance, the temporal dynamics of this process shows one important feature, that technological change follows an evolutionary course and that it may be possible to steer the course of development of technology in a "desirable" way by influencing the selection environment.[20] Two key theoretical insights about technological change that need to be highlighted here are the cumulative and evolutionary nature of this process. Ideas, practices, theories, and laws from the past do pass on to the development of newer technologies (Layton, 1974). The reason why this aspect tends to be neglected, or does not seem apparent, is due to the tacit nature of technological knowledge (Vincenti, 1990).

In shaping technological trajectory, the "selection" process is characterized by instruction, understanding, experience of learning by doing, and, finally, cognitive

[20] Schot (1992) presents an innovative approach to influencing and shaping the selection environment for the development of "cleaner" and "safer" technologies by using the methodology of "constructive technology assessment".

change. The term "evolution" is used in this context as an explanatory metaphor or meta-model. Technological change is construed as a selective-retention process that is adapted to a sequential process of variation and selection.[21] Within the milieu of socio-cultural evolution, adaptive learning and perception lead to the accumulation and change of technological knowledge. The evolutionary concept is important in explaining technological change because it captures the temporal nature of this phenomenon.

The cumulative nature of technological change, on the other hand, implies that technological change is irreversible. By cumulative, it is not meant a theory of accretion of everything past from that particular technological trajectory. The major idea here is that the functional attributes and basic design principles and operational guidelines of a technological system, to a large extent, remain invariant. In the physical and biological sciences, paradigmatic changes may occur due to new experimental discoveries and revolutionary theoretical advances. However, in the case of technology its fundamental functional attributes remain more or less invariant. The functional attributes of the technology remain invariant until a radically different technological paradigm inaugurates a new technological trajectory (Dosi, 1982; Constant, 1973).[22] Old and new technological paradigms do co-exist, and it is rarely a case that the old trajectory becomes totally extinct when the new trajectory is formed. Technological change is fundamentally influenced and moulded by its antecedents in a path-dependent way (Rosenberg, 1994). The idea of technological improvement as a means for efficient action remains the same in all societies. That is, more out of less. Improved efficiency, increased productivity, less cost, less human intervention for avoiding hazardous conditions, and so forth are achieved by improving on the existing technologies. Therefore, it is important that all models of technological change must account for both the cumulative and evolutionary nature of this process.

From the above vantage point, technological change can be characterized as a problem-solving activity. Although it is a problem solving activity conducted in need-based or need-induced circumstances, the solutions do not simply appear on a technology shelf, as often postulated in the production function model of technological change in neo-classical economics (Sahal, 1981). Extant political, economic, social, and institutional factors, including government policies, organize the problem-solving activity, but by themselves, do not provide the solutions. The technological problems vary from one situation to another and their solutions vary according to the degree of complexity of the technological system. Some of the technological problems are low efficiency, adverse environmental conditions, simple functional failures, imbalances between artifacts of different vintages, and inadequate organizational structures. These problems can be the direct or indirect result of climatic and geographic constraints, natural disasters, social and cultural demands for change, simple economic wants, military demands, varying resource positions, and other contingent factors.

The selection environment was moulded by the combined efforts of the international donor agencies, Third World governments, and the international and national research institutes. The transfer, diffusion, location specific adaptation, and the indigenous development of the new technological knowledge, ultimately, transformed the existing "traditional" knowledge system, in areas where the Green Revolution made a lasting impact. The case clearly delineates an active selective-retention process at different stages of learning by doing. There evolved a technological algorithm of how new knowledge could be utilized in the transformative process of increasing productivity of the material output, in this case into food.

The technological algorithm evolved as a means for simplifying the complex knowledge of a new agricultural system into a simplified form that farmers and peasants could easily understand in order to produce the desired results. In simple terms, it can be equated to a decision-rule-making process that includes all the protagonists associated with the Green Revolution. The role of the government and international bilateral and multilateral agencies was to create a proper selection environment for the technology users and developers, in this case, peasants-farmers, local

[21] The intellectual foundation for this evolutionary epistemology was first presented in Campbell (1974), who followed the pioneering works of Popper on the evolutionary nature of knowledge creation and its change.

[22] This, however, does not preclude the interpretative flexibility of old and new technologies because of the enrollment of new actors into the network (Bijker, 1995; Bijker and Law, 1992).

extension workers, and research and development personnel. Unlike natural selection, where chance occurrences are the norm, in technological selection, persuasion and the perception of the need for the new knowledge, decide the outcome. The possibilities for variation are limited and fixed, ex ante, to a large extent. As a result, the public agencies can guide the path of selection in most instances. The technological change involved new ways of doing things. However, the fundamental nature of agricultural practice did not change. The changes related to using new seeds and seed preparation, weeding and using chemical pesticides, watering, fertilizer application, and other such activities. Droughts and other "natural" disasters, inadequate organizational structures, pre-industrial technologies, social and cultural demands for change, simple economic wants, and the varying resource positions of regions and states were the problems that influenced the variation processes for the selection of the Green Revolution package of technology within the larger political economic context of the Cold War.

4. The Gene Revolution and its dynamics

4.1. The Gene Revolution in agriculture

The increase in productivity associated with the Green Revolution began to taper off in the 1980s (Conway, 1998; Strauss, 2000). Advances in cellular and molecular biology have opened up new vistas in agricultural technology since the mid-1970s, with particular impetus being felt during the 1990s because of advances in genomics spurred on by computers and information technology. The landmark scientific events in modern biology in general, and biotechnology in particular, were the rediscovery in 1900 of Gregor Mendel's revolutionary work on the genetic basis of inheritance, the identification of DNA as the physical carrier of genetic information by Max Delbruck in 1938, the discovery of the double helical structural model of the DNA molecule by James Watson and Francis Crick in 1953, and the recombinant DNA experiments pioneered by Stanley Cohen and Herbert Boyer in 1973 (Ruttan, 2001, pp. 370–374). The landmark Cohen–Boyer genetic experiments became the basis for recombinant DNA (r-DNA) technique, which enabled the splicing of genes by transferring genes (genetic information) from one organism into another.[23] McMillan et al. (2000) claim that the "biotech revolution" started in 1973 when the Cohen–Boyer r-DNA technique was invented. According to Kenney (1986, p. 23), the Cohen–Boyer gene splicing invention "was the single pivotal event in the transformation of the 'basic' science of molecular biology into an industry." However, the commercial significance of these new biotech innovations did not materialize until 1980 when the US Supreme Court extended patent protection to genetically modified organisms with its landmark ruling on Diamond versus Chakrabarty.

Although the claim that the "Gene Revolution"[24] in agriculture began in 1973 is understandable given the invention of the r-DNA technique in that year, the actual impact of the invention was felt only in the late 1970s with the unprecedented flow of scientific knowledge from the academy to the biotech industry. The strong knowledge network forged between major research universities and biotech corporations paved the way for the genetic revolution in modern biotechnology. The biotech revolution gained momentum in the early 1980s when large corporations began investing huge amounts of R&D capital for developing transgenic crops with the above scientific and technological advances acting as powerful knowledge base and selection environment for innovation and technology development. The selection environment was shaped by the huge influx of private capital and the unprecedented technology transfer arrangements between industry and university. Paarlberg (2000b) argues that the green signal for corporate investment in genetic technology came only after governments like the US extended intellectual property protection to transgenic organisms. Some experts claim that consequently a "Second Green Revolution" or a "Doubly

[23] See Cohen et al. (1973). The Cohen–Boyer r-DNA technique was described in the US Patent no. 4,237,244 issued to them in 1980 as "Process for Producing Biologically Functional Molecular Chimeras" (Kloppenburg, 1988, pp. 193–194).

[24] Unlike an authoritative source for the naming of the "Green Revolution" (see footnote 10), it is difficult to ascertain who came up with the term "Gene Revolution". The term appears in Serageldin (1999b), among other sources. Buttel et al. (1985) used the term "biorevolution" to signify the political economy of this staged transition from the Green Revolution.

Green Revolution" (Conway, 1998) began with the marriage of genetic engineering and modern agricultural practices. However, I will show that the Gene Revolution is not a continuation of the Green Revolution. They follow different systems of innovation and trajectories of technology development and diffusion.

Breeding steps using modern plant engineering techniques is a straightforward and clinical process than the trial and error process involved in the Green Revolution. While traditional selective breeding techniques improve the quality and yields of crops, genetic engineering techniques enable direct manipulation of plants through inserting, altering, or removing genes for specific purposes. Genetic engineering is a controlled mechanism involving precision and rigour, while traditional plant breeding involves trial and error that may involve the transfer of unwanted genes to the host organism (Nielson et al., 2001). Genetic technologies share a qualitative superiority over conventional methods of plant breeding because they can bypass the conventional method's reliance on sexual means to transfer genetic information (Kloppenburg, 1988). Genetic technologies "permit the modification of living organisms with an unprecedented specificity and allow a qualitatively different degree of genetic transformation" (Kloppenburg, 1988, p. 3).

There are essentially two techniques in modern biotechnology for plant breeding—molecular markers and genetically engineering transgenic crops. Molecular markers involve identifying specific genes from the DNA sequences in plant genomes with specific traits. Molecular marker tools are then used to screen varieties of plants for genes that confer resistance to specific diseases. Using this technique, plant breeders speed up the development of new varieties with the desirable traits (Arends-Kuenning and Makundi, 2000).

In genetic engineering, first the required objectives are determined in advance, such as resistance to pests, salinity, drought and so on, or improving nutritional levels, or delivering vaccines. The next step is to identify the sources of a gene in plants, animals or fungi that would offer solution to the particular problem being identified. The gene is isolated and its sequence is decoded to understand the structure of the gene and, if necessary, to redesign the gene to suit the new environment. The isolated gene is inserted into a single cell nucleus of the target plant and develops the cell into complete plants. The new transgenic plants are tested in isolated environment for resistance and other characteristics before commercial application. This technique is controversial because genes that confer the specific traits may come from different plant species or even from animals or virus. Well-known transgenic crops are *Bt*-corn, roundup ready soybean, and "Golden Rice".[25] Plant breeding in this new biotechnology is aimed at addressing specific needs, such as increasing tolerance to herbicides and pesticides, creating tolerance to drought or salinity or pests, and delivering vaccines and nutrients, unlike increasing crop yield as the primary concern in the Green Revolution.

The US is by far the biggest adopter of genetically engineered crops, almost three-fourths of the total crop area devoted to GM crops, while the other major producers are Argentina, Canada, and China (Nielson et al., 2001). Global area of transgenic crops planted in 1999 was 39.9 million ha, of which the US (72%), Argentina (17%), and Canada (10%) are the principal global GM crop producers (James, 2001). Developing countries that conducted transgenic crop field trials included Argentina, Belize, Bolivia, Chile, China, Costa Rica, Cuba, Egypt, Guatemala, India, Malaysia, Mexico, South Africa, Thailand, Turkey, and Zimbabwe

[25] The bacterium *Bacillus thuringiensis* (*Bt*) produces crystalline proteins that kill pests and hence the transfer of the specific genes from this bacterium confers insecticide property to corn, cotton and other crops (Conway, 1998, p. 152). The *Bt* gene induced toxin is claimed to be lethal to certain pests (such as stem borers), but not to humans and other organisms in the ecosystem. Roundup Ready soybeans developed by Monsanto have a gene added that confers tolerance to Monsanto herbicide Roundup (glyphosate) that kills several types of weeds (Paarlberg, 2000b). The so-called "Golden Rice" variety was developed by Ingo Potrykus and colleagues at the Swiss Federal Institute of Technology in Zürich by engineering the provitamin A (β-carotene) through a biosynthetic pathway into carotenoid-free rice endosperm. The golden hue of the rice is due to the β-carotene in the endosperm. For details of the engineering process, see Ye et al. (2000). Although developed by scientists working at publicly supported universities with partial funding from the Rockefeller Foundation, ironically, some seventy or so patents on various gene segments, sequencing processes and other developmental techniques used for creating this rice variety are held by private agro-biotech companies. At the final count Zeneca Agrichemicals, now known as Syngenta (largest biotechnology company in the world after merging with the agricultural division of Novartis), owns "Golden Rice". For a detailed exposition of the controversy surrounding "Golden Rice" see Christensen (2000).

(James, 1997). Among developing countries, China and Argentina are by far the largest producers of GM crops. Experimental planting of GM plants and crops are increasingly being adopted in India, Mexico, Philippines, Thailand, and Brazil. Experimental trials and local adaptive research are currently going on “Golden Rice” to transfer the added nutritional capacity from this japonica variety into indica variety of rices (which are consumed by most Asians) at rice research stations in India, China, and the International Rice Research Institute in Manila (IRRI, 2000).

4.2. Globalization and the Gene Revolution

The modernization project characterized variously by such structural and functional categories as industrial capitalism (Marx), rationalization and bureaucratization (Weber), and systemic and functional differentiation (Parsons) underwent a qualitative change towards the end of 20th century. Industrial societies began to show structural transformation in their modes of interactive and intersubjective practices based on the notional possibilities of new technologies and modes of production centered on information and networks (Castells, 1996). This structural transformation of industrial societies is variously characterized, but most commonly, as “post-industrial society” (Bell, 1973), or as “informational capitalism” (Castells, 1996). In this new phase of capitalism knowledge became the most important factor of production as opposed to machines, labour, and natural resources, the predominant factors of production of the industrial society (Drucker, 1993).[26] The coming of the post-industrial society[27] coincided with the newest phase of economic globalization as well. The so-called “new economy” is characterized by flexible production and free movement of capital on a global scale.[28] Replacement of industrial capitalism by financial capitalism and the intensification of “free” trade on a global scale are the other features of globalization.

The new phase of globalization is in certain definite ways different from its previous forms of the 16th and 19th centuries (UNDP, 1999). The new era of globalization is marked by: (i) the emergence of *new markets* which link foreign exchange and capital markets on a global scale operating in real time or selected time, thus eliminating spatial differentials; (ii) strengthening of *new and old actors* like WTO, IMF and other supra-national entities that exercise authority over national governments of Third World countries; (iii) the rise of MNCs which enjoy greater economic and political power over economically weaker governments where they operate plants but often disregard environmental and labour norms that would often be deemed violations in their home bases; (iv) enactment of *new rules* such as multilateral agreements on trade, services and intellectual property backed by strong enforcement mechanisms; (v) proliferation of new technological tools, such as biotechnologies, information and communication technologies that co-ordinate market operations; (vi) the rise of a *network society* marked by structural changes in social morphology of regions connected by the new tools and markets; (vii) the rise of resistance movements, such as NGOs through better articulation of civil society norms; and (viii) the exclusion of large areas of the world (such as Africa) from the benefits of trade and technological innovation.[29] The emergence of genetic agriculture coincides with the newest phase of globalization while the Green Revolution was part of industrial modernity.

Public sector (governments and government supported institutions) and non-profit international research institutions, international donor agencies like the World Bank, and philanthropic institutions like the Ford and Rockefeller Foundations played the key roles in the invention, innovation and diffusion of Green Revolution technologies. Private sector actors, which are predominantly multinational corporations, play the leading role in the innovation and diffusion of agricultural biotechnology related to the Genetic Revolution. The technological trajectory is shaped by the imperatives of private property institutions,

[26] Of course capital, labour, and natural resource were the predominant factors in classical economics. Neo-classical economics dismissed natural resource (land) because of its perceived lack of marginal value in the production function.

[27] Other analysts characterize the age as post-Marxist, or post-capitalist, or post-modern, or post-Fordist.

[28] The neo-liberal position on globalization professes the free movement of all factors of production. But the free movement of labor is, ironically, not a reality yet for obvious reasons.

[29] More detailed exposition of these characteristics of contemporary globalization can be found in UNDP (1999), Castells (1996), and Held et al. (1999).

market forces, global finance, and transnational (and in certain cases national) regulatory institutions. The contingencies and imperatives of economic globalization shape the technological trajectory. New plants and crops are being developed not to solve problems of hunger and deprivation, but mostly to increase shareholder values of companies that have invested heavily in R&D efforts in the biotechnology sector. Consumer preferences are more important than farmer's rights and interests in the development and diffusion of genetic agricultural technology, and the trend is to develop technology suited for the interests of large biotech firms. Very little feedback and input is derived from public agencies and farmers in technological innovation in the Gene Revolution.

4.3. Dynamics of the technological trajectory in the Gene Revolution

The selection environment of genetic-based agro-biotechnology is being shaped by the investment decision of private biotech corporations, the tension between the public and private domains in matters related to property rights in life forms, regulatory battles, consumer rights activism, and resistance to technological development from sources within civil society. While "donor fatigue" (Anderson, 1998) and tightening of funds for public benefit scientific research (Alston et al., 1998) have reduced financial support for agriculture research in the public domain, private sector investment in agriculture R&D has been increasing at impressive rates in recent years. Six large agriculture biotechnology companies spent more than 75% of global research and development and other investment money in biotechnology in 1998 (Krattiger, 1999). Private corporations registered almost all transgenic crops approved for planting as proprietorial technology (James, 1998). The total annual budget for 1998 of 16 international agricultural research centers under the Consultative Group on International Agricultural Research (CGIAR) was only US$ 345 million, while a single biotechnology corporation increased its R&D expenditure to US$ one billion per year (James, 1999). Public sector investment in agricultural technology declined considerably since the 1980s as some Third World countries improved their food production and maintained "a long period of sustained growth" in production (Alston et al., 1998). The end of the Cold War and the rise of neo-liberal politics saw Western aid, particularly American aid, to Third World countries to decline in both real and absolute terms. The general consensus in the West is that markets are the best arbiters of technology development and selection, and that the government better get out of the way of the private sector. "Inappropriability of benefits," otherwise known as the market failure argument of public goods, is claimed as a major reason given for the decline in investment in agriculture R&D in the public domain (Alston et al., 1998).

The progressive removal of trade barriers in agricultural commodities sector with the arrival of a global trade regime under the World Trade Organization (WTO) since 1995 favoured the private sector players to invest in biotechnology. The liberalization of intellectual property rights of patents, copyrights and trade secrets in plants, animals, genetic knowledge, and traditional knowledge systems under the TRIPS[30] agreements favoured the rights of private investors in the biotechnology sector than small farmers and producers. This allowed large biotechnology multinationals with unlimited resources for R&D and new product development to reap monopoly benefits obtained through patenting engineered life forms and new protein molecules from hitherto unavailable intellectual property rights.[31] Padrón and Uranga (2001, p. 315) rightly argue that intellectual property protection to biotechnological inventions is "a burden too heavy for the patent system" to adjudicate and resolve.

Some factors that led to the increased role of the private sector in agricultural research systems in recent

[30] The GATT negotiations that concluded in the establishment of the WTO contained an Annex on Trade-Related Aspects of Intellectual Property Rights (the "TRIPS Agreement"). The TRIPS Agreement gives wide coverage to intellectual property protection to patents, copyright and neighboring rights, trademarks, geographical indications, industrial designs, layout-designs (topographies) of integrated circuits, and undisclosed information. For more details on the TRIPS Agreement, see World Intellectual Property Organization (1997), Chapter 28.

[31] The trend started when the US Supreme Court in the landmark Diamond versus Chakrabarty case upheld, by a margin of one vote, the patent on a genetically engineered oil-eating bacterium. The US Supreme Court ruled that "Everything under the sun made by man is patentable" (quoted in the Economist, 2001). The US statute on patent rights essentially became the norm for the rest of the world. As David (1993) argued, the US managed to impose its position on patents and trade rights at international forums because of its economic and political might.

time are: (i) the declining funding levels in most developing countries due to various internal and external factors (Alston et al., 1998); (ii) weak management and bureaucratic inefficiencies in the public research domain leading to budgetary cuts of research funds (Echeverria et al., 1996); (iii) the intensification and institutionalization of intellectual property rights at global levels, especially after the TRIPS Agreement, opening up potentially greater opportunities for private research investments over public investments in agricultural technology; (iv) the rapid pace of privatization and encouragement given to private competition with parastatals in agriculture input supply in many countries, and the growing commercialization of agriculture as a world-wide phenomenon and the great demand for purchased inputs as a result of increasing competition in domestic and international markets (Pray and Umali-Deininger, 1998); and, (v) the commodification of traditional knowledge in agriculture and the legal loopholes to treat traditional knowledge as intellectual commons unprotected by IPR statutes (Dutfield, 2000). And the spectacular advances in molecular biology overcame the final biological barrier to the entry of private capital in agro-biotech business, although the process had already set in motion with the advent of hybridization in plant breeding to commercialize seed production during the Green Revolution.

The technological trajectory of agro-biotechnology is highly influenced by the tension between the public and private domains in biotech innovation and knowledge creation. The concept of property and the easiness of appropriating publicly available knowledge, including the gold-rush mentality to patent and commoditize traditional knowledge of plants, farming systems, and living matter derived from the global intellectual commons, has become a powerful shaper of agro-biotechnology. The tendency to mediate the conflict between the public and private domains in biotechnological research through property rights at the expense of other important concerns like bio-diversity, distributive justice, cultural rights, and ecological stability will have tremendous impact on molding the future trajectory of agro-biotechnology. In understanding innovation and technology development one must pay adequate attention to the public and private aspects of technology (Nelson, 1989). Padrón and Uranga (2001) see the problem straddling both the production and consumption side of modern biotechnology. On the production side they argue that the biotechnology industry depends on public science more than other industries and the privatization of such public knowledge not only fosters free riding but also deters innovation in socially beneficial ways.[32] On the consumption side, they argue, regulatory issues become serious because biotechnology is not "just another step on the continuum of technological development," but rather "a radical change with profound ontological implications" (Padrón and Uranga, 2001, p. 318).

While globalization and the rise of the knowledge economy and MNCs are key agents in shaping agricultural biotechnology, in order to understand the dynamics of innovation and commercialization of the technology one needs to see the process through the theoretical lens of "reflexive modernity" (Giddens, 1991; Beck, 1997) and "world risk society" (Beck, 1999). Various "knowledgeable agents" reflexively shaping genetic technology through self-confrontation is a key facet of technology dynamics here, albeit the power of the agents is differentially distributed according to the norms of the political economy of global financial capitalism. An array of life-style choices available as a result of spectacular technological innovations fomenting doubts about the "natural order," and concurrently spawning "new ethical spaces" (Giddens, 1994) for individuals to engage in the debates concerning the very shaping of such innovations is at the heart of reflexive modernity (Kerr and Cunningham-Burley, 2000).

The very fact that there is more profit to be made in the trade of inputs in agriculture than the output is also an important consideration in the value chain of agro-biotechnology commoditization. That various industries catering to the input side (seeds, fertilizers, pesticides, finance, mechanical tools, and educational institutions) of the production function emerged as significant players is crucial to this commodification

[32] McMillan et al. (2000) present empirical evidence to show that public science, that is, knowledge originated from universities, research institutions, government laboratories, and so on played a critical role in the success of US biotechnology firms. For a detailed and systematic examination of the contribution of public science (knowledge authored at institutions conducting scientific research funded by the government) to industrial technology, see Narin et al. (1997).

process. The proprietary nature of genetic knowledge and agricultural processes at different stages of input–output matrix under the new trade regime in a growing “weightless economy” (Quah, 1997) of “informational capitalism” (Castells, 1996) makes it ever more attractive for private capital to venture in agricultural research systems for new product development.[33]

Another key agent that plays a vital role in shaping agro-biotechnology is social movement NGOs that oppose globalization and genetic technology. Environmental NGOs that oppose the release of genetically modified organisms (GMOs) into the environment and the production and distribution of genetically modified (GM) foods are important agents in regulating research and trade in agricultural biotechnology. Indigenous rights activists that oppose the commodification and piracy of traditional plants and agricultural knowledge, and farmers’ movements that oppose infringement on their right to owning and propagating seeds and farming systems are also influential, to some extent, in influencing the trajectory of biotechnology. For example, biotech giant Monsanto’s plan to commercialize its so-called “terminator” seeds using genetic use restriction technology (GURT) whereby farmers would be unable to save and use harvested seeds was shelved due to intense pressure from farmers worldwide (Wright, 2001). Consumers in developed nations, particularly in Western Europe are also important agents in shaping the policy agenda for technological innovation and the regulatory regime pertaining to GMOs and GM food (Paarlberg, 2000a; Grossman and Endres, 2000). The politically sensitive nature of genetic technology in Europe has a crucial bearing on shaping both the regulatory regime and technological innovation in agro-biotechnology in large Western production centers such as the US, Canada and Australia. In fact, Paarlberg (2000b) argues that the future of GM food and agro-biotech will be shaped by the looming confrontation between the US-based industry groups and European consumers.

The rather advanced and complex regulatory regime in developed countries is in stark contrast to the near absence of any meaningful regulatory system in developing countries. This is particularly serious because large developing countries such as China, India, Brazil, Mexico, Argentina, and Indonesia are seriously engaged in the production of transgenic crops and the consequences to public health and possible ecological concerns become secondary issues to these countries when contrasted to their concerns for economic growth through increased agricultural productivity. The successful decoding of the rice genome by the giant Swiss MNC Syngenta has raised alarms about the future course of plant breeding in this important food source for more than half of the humans in the world (Wade, 2002).[34] Plant breeding in the new agro-genetics innovation system appears to be directed for the commercial gains of large MNCs than for improving the food security of poor consumers in the Third World.

Finally, technological change in agro-biotechnology must be analyzed within the framework of technological risks in both local as well as global contexts. The trade in technology-related products have become global in nature and the transfer of technology is now increasingly within the province of MNCs as part of their global investment strategies. Because of the competition for foreign direct investment from Third World countries, MNCs are trying to find destinations where regulatory regimes (labour, environmental and consumer) and intellectual property rights are more to their favour. Therefore, the management of technological risks associated with agro-biotech must be formulated as a global risk management problem to be formulated and implemented and coordinated with international, regional, and local agencies. Ultimately, it boils down to issues of the governance of science and technology and constructing effective technology foresight tools and mechanisms, such as constructive technology assessment (CTA), environmental impact assessment (EIA) and sustainable development indicators (SDI). A proper way to getting started on these line of future actions would be to follow an effective precautionary principle that is not too lax and broad as private

[33] However, the material foundations of the “weightless economy” and “informational capitalism” cannot be denied or wished away as Law and Hetherington (2000) have eloquently argued.

[34] The important scientific journal *Science* (5 April 2002) published two separate works on sequencing the rice genome by scientific teams from China and Syngenta. Syngenta’s earlier controversial role in its acquisition of the “Golden Rice” may be the reason for its foray into rice genomics being watched with alarm by some concerned scientists. See, Wade (2002) and Christensen (2000) for details.

investors and MNCs prefer and not too narrow and restrictive as deep ecologists and anti-biotechnology activists want.[35] How to find that constructive middle ground where the promises of agricultural biotechnology could benefit all stakeholders (particularly poor farmers and consumers in the Third World) is an important agenda for technology policy development to meet the challenges and exigencies of economic globalization.

5. Discussion and conclusion

The Gene Revolution in agricultural biotechnology was not a natural follower of the technological trajectory of the Green Revolution. The innovation, development, and diffusion of agricultural technologies followed different paths because of being part of different global and national innovation systems. The technological paradigms of these two phases of biotechnology were shaped within different societal, political, economic, and epistemic contexts. Existing social, political, economic, and ecological conditions shape the manner in which new technologies are developed and disseminated. As shown earlier, the Green Revolution and the Gene Revolution followed different technological trajectories. However, as Kloppenburg (1988, p. 4) persuasively argued, "an understanding of the 'old' biotechnologies is a prerequisite to understanding of the 'new' biotechnologies". While the forces of industrial modernity shaped the Green Revolution within the context of post-colonial politics during the Cold War, the Gene Revolution is being molded by the contingencies of globalization and "intellectual capitalism" (Granstrand, 2000) which gives impetus to private ownership of agricultural knowledge and artifacts. State and other public sector agencies, international donor and research institutions, and other non-profit organizations played a decisive role in shaping the Green Revolution. Geo-strategic considerations emanating from the politics of hunger during the Cold War, the national aspirations of Third World governments to attain food self-sufficiency, and the goodwill of scientists and technologists were the catalysts in the technology development and transfer regime of the Green Revolution. The Green Revolution was shaped by the convergence principle embedded in the social morphology of modernity, where the idea of economic development and improved standard of living spreading to the Third World through state-led efforts to channel technology and development aid from the West reigned supreme. Although there was no Marshall Plan to modernize Third World economies, the contingencies of the Cold War prompted the West to find a quick technological fix to avert hunger-led insurrection and possible communist takeover of key Third World nations without demanding drastic changes in the social relations of production and distribution of their agrarian sector—putatively the crucial economic sector in which most people sought their sustenance. The technology transfer programme under the Green Revolution was a "success" in a circumscribed way of increasing food production. However, serious distributional, environmental, and occupational hazards were not addressed because these were not the priority of the developers and promoters of the technology.

The model of innovation system in the Green Revolution follows a non-traditional global–local innovation system involving governments and public agencies, universities, and private international charitable agencies. Instead of industry acting as the third element of the usual innovation structure, we have non-profit international charitable organizations acting as agents of technology development and diffusion. Although there was some feedback received from farmers and local extension agents in the innovation process at a later stage, the innovation system may still be reconfigured in a trilateral mode.[36] Despite the active role of certain important societal agents (farmers, extension agents and consumers) in the innovation network of the Green Revolution, they did not, however, become an autonomous agent to

[35] The precautionary principle included in the Biosafety Protocol adopted by the United Nations Convention on Biological Diversity (CBD) in Cartagena in 1999 and Montreal in 2000 should be the basis for biotechnology development. CBD adopted the same text of the precautionary principle included in the 1992 Rio Declaration: "Where there are threats to serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation," quoted in Adler (2000, p. 194).

[36] This trilateral reconfiguration may be undertaken within the "NIS" or "NAIS" mode of agricultural innovation, as described in footnotes 8 and 9.

be categorized as a fourth element of the innovation system.[37]

Considerations of private gain and profit in the form of high returns to shareholders of agro-biotech companies of global reach determine the dynamics of technological innovation in the Gene Revolution. As Arends-Kuenning and Makundi (2000, p. 333) argue, the crops and plant traits developed under such regime "will be the ones expected to make the largest profits". The imperatives of global financial architecture, unrestricted trade, and unhindered rights of intellectual property in life forms and organic molecules, and global risk concerns under the juggernaut of economic globalization are the catalysts of technology development in the Gene Revolution. Technological innovation, development, and transfer in the agro-biotech sector are being influenced by the tension between the public and private domains where the asymmetry in power relations in favour of the former until recently is now tilting towards the latter.

The technological trajectory will be affected significantly by the success in mediating between the public and private domains by de-centring the primacy of IPR regime in biotechnology research. Ways must be found to adapt the IPR regime such that innovations in agro-biotechnology could be stimulated through new institutional frameworks that encompass broader social goals than patents and private gain. As Peter Drahos (1999, p. 443) puts it eminently, "such adaptation must be governed by the public purpose that is embedded in patent law and the broader public ethic, rather than by private purposes". Instead of the present trend of proprietarianism in IPR, an instrumental attitude should prevail because there is nothing essentialist about private property (Drahos, 1996), other than it being a socially constructed entity that is mediated and moulded by prevailing social relations. As one observer puts it imaginatively, "Focusing on the problems of justifying intellectual property is important not because these institutions lack any sort of justification, but because they are not so obviously or easily justified as many people think. We must begin to think more openly and imaginatively about the alternative choices available to us for stimulating and rewarding intellectual labor" (Hettinger, 1989: 52).

Biotechnology should be treated as a primary good containing a basket of information and artifacts crucial for human well being, such that public or private efforts to create artificial scarcity in the domain through unjustified regulation or unconditional enclosing of this intellectual commons could be thwarted. Setting the research agenda in biotechnology sector should not be left to the marketplace or the Leviathan alone. Using the presently construed "Triple-Helix" of government–industry–academe model of global and national system of innovation to self-organize and self-govern itself for the larger public good is inadequate. To understand the complexity of the technological trajectory in agricultural biotechnology, we should look at the innovation system made up of government, academe, industry, *and* NGOs. Because of the important role NGOs (both formally organized social groups as well as unorganized general public concerned about biotechnology) play as a key stakeholder in (re)shaping biotechnology in recent times through resistance and regulatory pressure as shown in this article, the innovation system should be re-conceptualized to include this key societal agent. How such an innovation model should be configured is an important research problem for another occasion.[38]

Acknowledgements

An earlier version of this article was presented in a colloquium at the Institut für Geschiste, Departement für Geistes-, Sozial- und Staatswissenaschaften, Swiss Federal Institute of Technology Zürich on 2 February 2001. Comments and suggestions for improvement of the manuscript from the editor, Michel Callon, and two anonymous referees of *Research Policy* are gratefully acknowledged. Thanks are also extended to Greg Felker, Robert Ferguson, and T.T. Sreekumar for constructive comments on an early draft of the article.

[37] This is in contrast to the fourth significant agent made up of NGOs which played a key role in shaping the Gene Revolution. This significant player should be added to the existing trilateral models to form a quadruple helix. Mehta (2002) argues that this fourth helix should be called the "public".

[38] A preliminary thought on this point is to develop a quadruple helix of state–university–industry–NGOs relationship, bearing in mind the extremely complex nature of the interactive relationships in such a structural configuration.

References

Acs, Z., de la Mothe, J., Paquet, G., 2000. Regional innovation: in search of an enabling strategy. In: Acs, Z. (Ed.), Regional Innovation, Knowledge and Global Change. Pinter, London, pp. 37–52.

Adas, M., 1989. Machines as the Measure of Men: Science, Technology, and Ideologies of Western Dominance. Cornell University Press, Ithaca, NY.

Adler, J.H., 2000. More sorry than safe: assessing the precautionary principle and the proposed international biosafety protocol. Texas International Law Journal 35, 173–205.

Alston, J.M., Pardey, P.G., Roseboom, J., 1998. Financing agricultural research: international investment patterns and policy perspectives. World Development 26 (6), 1057–1071.

Anderson, J.R., 1998. Selected policy issues in international agricultural research: on striving for international public goods in an era of donor fatigue. World Development 26 (6), 1149–1162.

Arends-Kuenning, M., Makundi, F., 2000. Agricultural biotechnology for developing countries: prospects and policies. American Behavioral Scientist 44 (3), 318–349.

Beck, U., 1992. Risk Society: Towards a New Modernity. Sage, London.

Beck, U., 1997. The Reinvention of Politics: Rethinking Modernity in the Global Social Order. Polity Press, Cambridge.

Beck, U., 1999. World Risk Society. Polity Press, Cambridge, UK.

Bell, D., 1973. The Coming of Post-Industrial Society: A Venture in Social Forecasting. Basic Books, New York.

Bijker, W.E., 1995. Of Bicycles, Bakelites, and Bulbs: Towards a Theory of Sociotechnical Change. MIT Press, Cambridge, MA.

Bijker, W.E., Law J., (Eds.), 1992. Shaping Technology/Building Society: Studies in Sociotechnical Change. MIT Press, Cambridge, MA.

Binswanger, H., Ruttan, V.W., 1978. Induced Innovation: Technology, Institutions and Development. Johns Hopkins University Press, Baltimore.

Buttel, F.H., Kenney, M., Kloppenburg, J.R., 1985. From green revolution to biorevolution: some observations on the changing technological bases of economic transformation in the Third World. Economic Development and Cultural Change 34 (1), 31–55.

Callon, M., 1987. Society in the making: the study of technology as a tool for sociological analysis. In: Bijker, W.E., Hughes, T.P., Pinch, T., (Eds.), 1987. The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology. MIT Press, Cambridge, MA, pp. 83–106.

Campbell, D.T., 1974. Evolutionary epistemology. In: Schlipp, P.A. (Ed.), The Philosophy of Karl Popper. Open Court, La Salle, IL, pp. 413–463.

Castells, M., 1996. The Rise of the Network Society. Blackwell Scientific Publishers, Malden, MA.

Christensen, J., 2000. Golden Rice in a Grenade-Proof Greenhouse. The New York Times, 21 November, pp. D1 and D5 (Science Times).

Cohen, S., Chang, A., Boyer, H., Helling, R., 1973. Construction of biologically functional bacterial plasmids in vitro. Proceedings National Academy of Science USA 70, 3240–3244.

Constant, E., 1973. A model of technological change applied to the Turbojet Revolution. Technology and Culture 14, 553–572.

Conway, G., 1998. The Doubly Green Revolution: Food for All in the Twenty-First Century. Cornell University Press, Ithaca, NY.

Dalrymple, D.G., 1979. The adoption of high-yielding grain varieties in developing nations. Agricultural History 53 (4), 704–726.

Dalrymple, D.G., 1986. Development and Spread of High-Yielding Wheat Varieties in Developing Countries. US Agency for International Development, Washington, DC.

Dalrymple, D.G., 1988. Changes in wheat varieties and yields in the United States, 1919–1984. Agricultural History 64 (4), 20–36.

David, P.A., 1993. Intellectual property institutions and the Panda's thumb: patents, copyrights, and trade secrets in economic theory and history. In: Wallerstein, M.B., Mogee, M.E., Schoen, R.A. (Eds.), Global Dimensions of Intellectual Property Rights in Science and Technology. National Academy Press, Washington, DC, pp. 19–61.

Dawson, A.C., 1998. The intellectual commons: a rationale for regulation. Prometheus 16 (3), 275–289.

Dosi, G., 1982. Technological paradigms and technological trajectories. Research Policy 11 (3), 147–162.

Drahos, P., 1996. A Philosophy of Intellectual Property. Dartmouth, Aldershot, UK.

Drahos, P., 1999. Biotechnology patents, markets, and morality. European Intellectual Property Review 9, 441–449.

Drucker, P.F., 1993. Post-Capitalist Society. HarperBusiness, New York.

Dutfield, G., 2000. The public and private domains: intellectual property rights in traditional knowledge. Science Communication 21 (3), 274–295.

Echeverria, R.G., Trigo, E.J., Byerlee, D., 1996. Institutional change and effective financing of agricultural research in Latin America. World Bank Technical Paper No. 330. World Bank, Washington, DC.

Economist. 2001. Patently absurd. The Economist Quarterly (5) 36–40.

Escobar, A., 1995. Encountering Development: The Making and Unmaking of the Third World. Princeton University Press, Princeton.

Etzkowitz, H., Leydesdorff, L., 1997. A Triple Helix of University–Industry–Government Relations. Cassell Academic, London.

Etzkowitz, H., Leydesdorff, L., 2000. The dynamics of innovation: from National Systems and "Mode 2" to a Triple Helix of university–industry–government relations. Research Policy 29, 109–123.

Freeman, C., 1987. Technology Policy and Economic Performance: Lessons from Japan. Pinter, London.

Giddens, A., 1991. Modernity and Self-Identity. Polity Press, Cambridge.

Giddens, A., 1994. Living in a Post-industrial Society. In: Beck, U., Giddens, A., Lash, S. (Eds.), Reflexive Modernization: Politics, Tradition and Aesthetics in the Social Order. Polity Press, Cambridge, pp. 56–109.

Granstrand, O., 2000. The shift towards intellectual capitalism—the role of infocom technologies. Research Policy 29, 1061–1080.

Grossman, M.R., Endres, A.B., 2000. Regulation of genetically modified organisms in the European Union. American Behavioral Scientist 44 (3), 378–434.

Guerinot, M.L., 2000. The Green Revolution strikes gold. Science 287 (1), 241–243.

Hall, A., Clark, N., Rasheed, S.V., Sivamohan, M.V.K., Yoganand, B., 2000. New agendas for agriculture research in developing countries: policy analysis and institutional implications. Knowledge, Technology and Policy 13 (1), 70–79.

Hall, R., 1957. Epilogue: the rise of the west. In: Singer, C., et al. (Eds.), A History of Technology, vol. III. Oxford University Press, Oxford.

Held, D., McGrew, A., Goldblatt, D., Perraton, J., 1999. Global Transformations: Politics, Economics and Culture. Stanford University Press, Stanford.

Hettinger, E.C., 1989. Justifying intellectual property. Philosophy and Public Affairs 18 (1), 31–52.

Hughes, T.P., 1983. Networks of Power: Electrification in Western Society, 1890–1930. Johns Hopkins University Press, Baltimore.

Hughes, T.P., 1986. The seamless web: technology, science, etcetera, etcetera. Social Studies of Science 16, 281–292.

Hughes, T.P., 1987. The evolution of large technological systems. In: The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology. MIT Press, Cambridge, MA, pp. 51–82.

IRRI, 2000. The Reward of Rice Research, Annual Report 1999-2000. International Rice Research Institute, Manila.

James, C., 1997. Global Status of Transgenic Crops in 1997. ISAAA Briefs No. 5, International Service for Acquisition of Agri-biotech Applications, Ithaca, NY.

James, C., 1998. Global Review of Commercialized Transgenic Crops: 1998. ISAAA Briefs No. 8, International Service for Acquisition of Agri-biotech Applications, Ithaca, NY.

James, C., 1999. Global Status of Commercialized Transgenic Crops: 1999. ISAAA Briefs No. 12, International Service for Acquisition of Agri-biotech Applications, Ithaca, NY.

James, C., 2001. Transgenic crops worldwide: current situation and future outlook. In: Qaim, M., Krattiger, A.F., von Braun, J. (Eds.), Agriculture Biotechnology in Developing Countries: Towards Optimizing the Benefits for the Poor. Kluwer Academic Publishers, Boston, pp. 11–24.

Kenney, M., 1986. Biotechnology: The University–Industrial Complex. Yale University Press, New Haven.

Kerr, A., Cunningham-Burley, S., 2000. On ambivalence and risk: reflexive modernity and the new human genetics. Sociology 34 (2), 283–304.

Kloppenburg, J.R., 1988. First the Seed: The Political Economy of Plant Biotechnology, 1492–2000. Cambridge University Press, Cambridge.

Krattiger, A.F., 1999. Networking biotechnology solution with developing countries: the mission and strategy of the International Service for the Acquisition of Agri-Biotech Application. In: Hohn, T., Leisinger, K.M. (Eds.), Biotechnology of Food Crops in Developing Countries. Springer-Verlag, Vienna, pp. 25–33.

Kuhn, T.S., 1970. The Structure of Scientific Revolutions. University of Chicago Press, Chicago.

Latour, B., 1987. Science in Action: How to Follow Scientists and Engineers Through Society. Harvard University Press, Cambridge, MA.

Latour, B., 1988. The Prince for machines as well as for machinations. In: Elliott, B. (Ed.), Technology and Social Processes. Edinburgh University Press, Edinburgh, pp. 20–43.

Law, J., 1987. On the social explanation of technical change: the case of the Portuguese maritime expansion. Technology and Culture 28 (2), 227–252.

Law, J., Hetherington, K., 2000. Materialities, spatialities, globalites. In: Bryson, J.R., Daniels, P.W., Henry, N., Pollard, J., (Eds.), Knowledge, Space, Economy. Routledge, London, pp. 34–49.

Layton, E.T., 1974. Technology as knowledge. Technology and Culture 15 (1), 31–41.

Layton, E.T., 1989. Through the looking glass or, news from lake mirror image. In: Cutcliffe, S.H., Post, R.C. (Eds.), In Context: History and the History of Technology. Lehigh University Press, Bethlehem, PA, pp. 29–41.

Lele, U., Goldsmith, A.A., 1989. The development of national agricultural research capacity: India's experience with the Rockefeller Foundation and its significance for Africa. Economic Development and Cultural Change 37 (2), 305–344.

Leydesdorff, L., 2000. The triple helix: an evolutionary model of innovations. Research Policy 29, 243–255.

Lundvall, B.-Å., (Ed.), 1992. National Systems of Innovation: Towards a Theory of Innovation and Interactive Learning. Pinter, London.

McMillan, G.S., Narin, F., Deeds, D.L., 2000. An analysis of the critical role of public science in innovation: the case of biotechnology. Research Policy 29, 1–8.

Mehta, M., 2002. Regulating biotechnology and nanotechnology in Canada: a post-normal science approach for inclusion of the Fourth Helix. In: Proceedings of the Paper Presentation at the International Workshop on Science, Technology and Society: Lessons and Challenges, National University of Singapore, 18–19 April 2002 (Mimeo).

Misa, T.J., 1992. Theories and models of technological change: parameters and purposes. Science Technology and Human Values 17, 3–12.

Narin, F., Hamilton, K.S., Olivastro, D., 1997. The increasing linkage between U.S. technology and public science. Research Policy 26, 317–330.

Needham, J., 1969. The Grand Titration: Science and Society in East and West. Allen & Unwin, London.

Needham, J., 1954-1988. Science and Civilization in China, vols. 1–7. Cambridge University Press, Cambridge.

Nelson, R.R., 1989. What is private and what is public about technology? Science, Technology and Human Values 14 (3), 229–241.

Nelson, R.R. (Ed.), 1993. National Innovation Systems: A Comparative Study. Oxford University Press, New York.

Nelson, R.R., 2000. National innovation systems. In: Acs, Z. (Ed.), Regional Innovation, Knowledge and Global Change. Pinter, London, pp. 11–26.

Nelson, R.R., Winter, S.G., 1977. In search of useful theory of innovation. Research Policy 6, 36–76.
Nielson, C.P., Robinson, S., Thierfelder, K., 2001. Genetic engineering and trade: panacea or dilemma for developing countries. World Development 29 (8), 1307–1324.
Padrón, M.S., Uranga, M.G., 2001. Protection of biotechnological inventions: a burden too heavy for the patent system. Journal of Economic Issues 35 (2), 315–322.
Paarlberg, R., 2000a. Promise or peril? Genetically modified crops in developing countries. Environment 42 (1), 19–27.
Paarlberg, R., 2000b. The global food fight. Foreign Affairs 79 (3), 24–38.
Parayil, G., 1992. The green revolution in India: a case study of technological change. Technology and Culture 33 (4), 737–756.
Parayil, G., 1998. The ‘revealing’ and ‘concealing’ of technology. Asian Journal of Social Science 26 (1), 17–28.
Parayil, G., 1999. Conceptualizing Technological Change: Theoretical and Empirical Explorations. Rowman & Littlefield, Lanham, MD.
Perkins, J.H., 1997. Geopolitics and the Green Revolution: Wheat, Genes, and the Cold War. Oxford University Press, New York.
Pinch, T., Bijker, W.E., 1987. The social construction of facts and artifacts: or how the sociology of science and the sociology of technology might benefit each other. In: The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology. MIT Press, Cambridge, MA, pp. 17–50.
Pray, C.E., Umali-Deininger, D., 1998. The private sector in agricultural research systems: will it fill the gap? World Development 26 (6), 1127–1148.
Quah, D.T., 1997. Increasingly weightless economies. Bank of England Quarterly Bulletin (2) 49–56.
Read, H., 1974. Partners With India: Building Agricultural Universities. University of Illinois Press, Urbana-Champaign.
Rosenberg, N., 1994. Exploring the Blackbox: Technology, Economics and History. Cambridge University Press, Cambridge.
Rosenberg, N., 1998. Uncertainty and technological change. In: Neef, D., Siesfeld, G.A., Cefola, J. (Eds.), The Economic Impact of Knowledge. Butterworth-Heinemann, Boston, pp. 17–34.
Rosenberg, N., Vincenti, W.G., 1978. The Britannia Bridge: The Generation and Diffusion of Technological Knowledge. MIT Press, Cambridge, MA.
Ruttan, V.W., 2001. Technology, Growth, and Development: An Induced Innovation Perspective. Oxford University Press, New York.
Sahal, D., 1981. Alternative conceptions of technology. Research Policy 10, 2–24.
Saxenian, A., 1994. Regional Advantage: Culture and Competition in Silicon Valley and Route 128. Harvard University Press, Cambridge, MA.
Saxenian, A., 2000. Regional Networks and Innovation in Silicon Valley and Route 128. In: Acs, Z. (Ed.), Regional Innovation, Knowledge and Global Change. Pinter, London, pp. 123–138.
Schot, J.W., 1992. Constructive technology assessment and technology dynamics: the case of clean technologies. Science, Technology and Human Values 17 (1), 36–56.
Serageldin, I., 1999a. From Green Revolution to Gene Revolution. Economic Perspectives 4 (4), October 1999, IIP E-Journals, US Department of State. At: http://usinfo.state.gov/journals/ites/1099/ijee/bio-serageldin.htm (accessed: 24 May 2002).
Serageldin, I., 1999b. Biotechnology and food security in the 21st century. Science 285 (16 July), 387–389.
Smith, M.E., Reber, S.C., 1989. Contextual contrasts: recent trends in the history of technology. In: Cutcliffe, S.H., Post, R.C. (Eds.), In Context: History and the History of Technology. Lehigh University Press, Bethlehem, PA, pp. 133–149.
Staudenmaier, J.M., 1985. Technology’s Storyteller: Reweaving the Human Fabric. MIT Press, Cambridge, MA.
Strauss, M., 2000. When Malthus Meets Mendel. Foreign Policy No. 119, Summer, pp. 105–112.
Thistle, 2001. Continuing the Green Revolution: The corporate assault on the security of the global food supply. The Thistle 13(4), June/July. At: http://web.mit.edu/thistle/www/v13/4/food.html (accessed: 24 May 2002)
Vincenti, W.G., 1984. Technological knowledge without science: the invention of flush riveting in American airplanes, ca. 1930–ca. 1950. Technology and Culture 25, 540–576.
Vincenti, W.G., 1990. What Engineers Know and How They Know It. John Hopkins University Press, Baltimore.
UNDP (United Nations Development Programme), 1999. Human Development Report 1999. Oxford University Press, New York.
Wade, N. 2002. Experts Say They Have Key to Rice Genes. The New York Times, April 5, 2002 (http://www.nytimes.com/2002/04/05/science/05RICE.html)
World Intellectual Property Organization (WIPO), 1997. Introduction to Intellectual Property Theory and Practice. Kluwer Law International, London.
Wright, B.D., 2001. Intellectual property rights challenges and international research collaboration in agricultural biotechnology. In: Qaim, M., Krattiger, A.F., von Braun, J. (Eds.), Agricultural Biotechnology in Developing Countries: Towards Optimizing the Benefits for the Poor. Kluwer Academic Publishers, Boston, pp. 289–314.
Ye, X., Al-Babili, S., Klöti, A., Zhang, J., Lucca, P., Beyer, P., Potrykus, I., 2000. Engineering the provitamin A (β-carotene) biosynthetic pathway into (carotenoid-free) rice endosperm. Science 287 (14), 303–305.