Technological Forecasting & Social Change 100 (2015) 198–212

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

Emergence of controversy in technology transitions: Green Revolution and Bt cotton in India

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ARTICLE INFO

Article history:
Received 1 April 2014
Received in revised form 23 April 2015
Accepted 21 June 2015
Available online 28 July 2015

Keywords:
Technology transition
Controversy
Green Revolution
Genetically modified
Bt cotton
Agriculture
India

ABSTRACT

Technology transitions following radical technological breakthroughs are often marked by controversies and the transitions to Green Revolution (GR) and Genetically Modified (GM) seeds in India were no exceptions to this rule. Controversies can trigger social dilemmas, but in economics we do not yet have a clear understanding of how they emerge in the wake of major technological transitions. In order to provide insight, we develop a novel conceptual framework of technology transition integrating 'Nature' as a non-economic actor in the innovation system. Then this framework is applied to analyze India's GR and GM transitions in cereals and cotton respectively, using the methods of historical reconstruction, meta-analysis of impact literature and a farmer survey. We show that the trigger points of controversies were different in the two cases, and in general can emerge in any stage of a technology transition. In particular, in the agricultural innovation system, the ecological outcomes rather than economic outcomes are likely to be stronger focal points of controversy. Controversies are also likely to increase as the innovation system becomes complex. High immediate payoffs can override concerns founded on scientific uncertainty in the adoption of new technologies.

1. Introduction

Technological transitions, or paradigm shifts ushered in by radical innovations, are marked by uncertainty or a lack of complete and perfect information about possible outcomes. As a consequence, economic actors in the innovation system may not rank the different outcomes associated with a technology transition as they would in the absence of such informational constraints. At a macro level, in addition to preferences, informational constraints can lead to differences of opinion that escalate into prolonged public disagreements over technology choice. They may even become controversies posing a social dilemma, if there is a risk of misallocation of resources in promoting one option over another or if resources have to be channeled into consensus building in order to make a more informed choice. Hence, management of technology transitions without controversies are a challenge for policy makers, who have to spur economic growth through innovation generation while maximizing societal welfare. However, in economics, we do not yet have a clear understanding of how controversies emerge in the wake of radical technological breakthroughs and the paradigm shifts that follow.[1] Thus, the present paper aims to contribute to closing this gap through a detailed study of two recent technology transitions in the Indian agriculture sector.

In agriculture, once a plant type gains popularity, it is adopted widely and planted in multiple cropping seasons and suitable regions. Over a span of years, it becomes vulnerable to new pests and pathogens and eventually the yield of that variety comes down. This reality calls for continual investments in seed technology research to sustain agriculture productivity (Swanson, 2002; Peng et al., 1999; Peng et al., 2010). However, even if an innovation in the form of new plant variety offers a potential solution to improving productivity, it may not enjoy commercial success, unless it is accepted by key stakeholders in the innovation system. This could be due to controversies, which arise whenever there is a major conflict between the maintenance of 'land productivity', 'farmer livelihoods' and 'environmental preservation'. For governments, it is important to steer technology transitions in agriculture towards all three objectives, and for this, an understanding of controversies is essential.

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[1] A standard bibliometric search which was carried out in Scopus – Economics – citation database using the boolean string ('controversy') AND ('technology' OR 'technology transition' OR 'paradigm shift') in title, keywords and abstracts. The results yielded no journal articles that proposed theoretical frameworks to address the subject from an innovation systems perspective.

http://dx.doi.org/10.1016/j.techfore.2015.06.018
0040-1625/

The role of controversies in shaping technology transitions is an understudied topic, though it is widely acknowledged in innovation studies that it is not only the intrinsic technology characteristics that determine the scale of diffusion, but also the strategic positioning of key stakeholders vis-à-vis the innovation. In other words, while the 'why' of controversies in technology transitions can be explained as being due to mutually conflicting beliefs, the 'how' requires further examination. Thus, the objective of the present paper is to study how controversies emerge and influence technology transitions. For this purpose, a theoretical construct is formulated and thereafter validated through application to two technology transitions that have deeply marked Indian agriculture, namely the Green Revolution in cereals and genetically modified cotton.

The Green Revolution (henceforth GR) in Indian agriculture is widely acknowledged to have been responsible for chasing away the specter of famine which haunted India during the 1960s. As a technology package involving improved quality seeds, also termed 'modern variety' seeds, controlled irrigation and measured doses of fertilizers, GR was introduced in India through cooperation between international public agencies and Indian research laboratories. However, while GR technologies heralded a veritable increase in yields with respect to cereals, it left in its wake environmental concerns. Today, GR itself is felt to be yellowing and in its place, rejuvenation of the agriculture sector is being promised by a new technology paradigm, namely genetically modified plant varieties. Transgenic or genetically modified (henceforth GM) crops[2] were developed by the application of modern biotechnology to agriculture. As in GR modern varieties, GM plant varieties were also introduced through technology collaboration with foreign organizations. Only this time, the transfer took place entirely between private sector entities. Genetic engineering of plants, according to its protagonists, promises even greater advantages than GR technology, but according to its opponents, presents even greater ecological risks.

Examining the above context, the present paper makes two types of contributions to the economics of innovation literature. First, it offers a conceptual framework for studying technological transitions in agriculture combining the innovation systems perspective with a game theoretic approach. In particular, it includes Nature or ecology as an actor in the innovation system — a novelty with respect to standard innovation studies. Second, it provides new insights on how major controversies can arise by applying the conceptual framework to analyze GR and GM transitions in Indian agriculture. In the case of emerging technologies shrouded in uncertainty, our case studies illustrate that the confrontation of scientific uncertainty and perceived uncertainty lies at the foundation of controversies. Further, in agriculture, controversies are triggered by concerns about ecology rather than profits. At the same time, controversial technologies can enjoy success with adopters, if they are associated with immediate higher payoffs. The likelihood of controversy is determined by the characteristics of the innovation system in which it is embedded and our case studies indicate that as an innovation system gets more complex, the likelihood of controversy increases.

The remainder of our paper is organized as follows. Section 2 outlines the methodology. Section 3 introduces our conceptual framework. Section 4 contains three types of validation of our theoretical construct. Finally, Section 5 concludes with a discussion of our results and policy recommendations.

[2] "Genetically modified (GM) crops are those that have been genetically enhanced using modern biotechnology to carry one or more beneficial new traits. Modern biotechnology as defined by the Cartagena Protocol on Biosafety as a means the application of: (a.) In vitro nucleic acid techniques, including recombinant deoxyribonucleic acid (DNA) and direct injection of nucleic acid into cells or organelles, or (b.) Fusion of cells beyond the taxonomic family, - that overcome natural physiological reproductive or recombination barriers and that are not techniques used in traditional breeding and selection" (Biotechnology, in, International Seed Federation) Biotechnology, in, International Seed Federation.

2. Methodology

We apply a mixed methodology to answer our central questions of how controversies emerge and influence technology transitions. A theoretical construct of technology transitions in agriculture is first developed. Then it is validated using qualitative research methods. A three stage procedure comprising historical reconstruction of GR and GM transitions in India, analysis of impact literature and survey of Bt cotton farmers is applied. At each stage, results are inferred, and then in the final section, they are combined together to provide a broader analytical insight for the management of controversies in other sectors as well. Multiple sources of data, both primary and secondary, are used to construct our arguments. This multipronged research strategy provides a strong empirical base for the validation of our framework and to arrive at results that constitute a grounded theory (Glaser and Strauss, 2009).

The theoretical construct developed in this paper draws upon the evolutionary economics literature on technology transitions. Using this framework, the history of the introduction of the two radical technological innovations in Indian agriculture is reconstructed in order to understand the role of the different actors, their strategies and the outcomes of their strategies. The case study method is applied, because it is suitable for identifying the 'how' of phenomena (Yin, 2002; Eisenhardt, 1989).

A second validation is carried out through a meta-analysis of the socio-economic impact of GR and GM. The corpus is constructed by looking into the economics literature as well as Government and NGO reports. The focus of the meta-analysis is to identify if there are any differences in findings about the ecological and economic impacts of GR and GM transitions.

A third application of our framework consists of a survey of Bt cotton farmers to discern impact perceptions. Given that controversies on Bt cotton are centered on economic and ecological outcomes, the farmer survey provides us the necessary critical complementary insights. The survey applies a semi-structured questionnaire designed to yield information on personal experiences with Bt cotton.

At this juncture, some limitations of our methodology and approach are acknowledged. An axiomatic theoretical construct can only serve to illustrate a phenomenon or a theory, but does not constitute a theory in itself. Similarly, while case studies are useful to understand processes, they can only give indicators of cause and effect. These important points have been kept in mind while drawing inferences. With respect to a comparison of GR and GM in India, a variety of crops were improved and commercialized under GR as opposed to only cotton under GM. Furthermore, cotton is a cash crop and resistance to a class of pests via transgenes is only one technological solution among the many offered by the emerging GM paradigm. Despite these differences, the dynamics of their diffusion have been compared as they yield valuable insight on our research query. On another note, the primary data used to validate our model is based on a survey of 127 farmers who have adopted GM cotton in India. While this sample is not representative of the thousands of Indian farmers growing GM cotton, we do believe that it is adequate for testing the conceptual framework developed in the present paper.

3. A theoretical construct

3.1. Innovation system and characteristics of agricultural production

In economics, technology is given by efficient input-output combinations, where efficiency signifies that the set of inputs represents the minimum amount of each input (in that combination) required to produce the associated output. Technologies emerge and evolve within the national and sectoral systems of innovation. A national system of innovation refers to the structure and functioning of a system comprising economic actors who are responsible for the creation, development, diffusion and adoption of innovations within a country (Lundvall, 1992; Nelson, 1993; Freeman, 1995). The sectoral system of innovation incorporates sectoral specificities in an innovation system which go beyond national borders (Lee and Lim, 2001; Malerba, 2002).

The evolution of technology in any sector can be considered to be the outcomes of games played within an innovation system between players whose strategies are interdependent, and whose choices jointly determine final outcomes. The main players in an innovation system are usually the state, public agencies, universities, public laboratories, firms, financial organizations, non-governmental organizations, civil society groups and consumers. Each actor in the innovation system has a set of targeted objectives, a resource portfolio, beliefs, cognitive structures, a knowledge and information base, and constraints. The constraints might take the form of limited scope of actions, limited resources and skills, and informational constraints (i.e. an incomplete or imperfect information base). Each actor chooses its strategy so as to move closer to its objectives, given its constraints. At the same time, players' actions are shaped by the rules of the game at the systemic level, i.e. the common habits, routines, established practices, rules or laws that regulate the relations and interactions between individuals, groups and organizations, which are generated by institutions in the system (Edquist, 2001).

The game of technology transition is marked by sectoral specificities. For instance, standard representations of the agriculture system of innovation include farmers, private input suppliers (i.e. firms supplying seeds, chemicals, equipment etc.), public agencies, distributors, retailers, consumers and the state as the main players. In addition, we propose that Nature must also be considered as a non-economic actor in the agriculture innovation system for two reasons. First, the flows of outcome variables such as yield, revenues, costs and even knowledge transfers depends on the state of Nature via agricultural productivity. Indeed, agricultural productivity depends on environmental factors such as soil quality, temperature, and pest incidence. These factors are just as important to the production process as other standard inputs like land, labor, water and nutrients. Second, farmers change the state of Nature through their choice of technology and implementation practices. For instance, farmers constantly change the bio-physical elements such as soil, pests, air and water through their production activities, which may not only affect their own farms, but also those of others.

At the same time, as a player in the innovation system, Nature is distinct from other economic actors. While the play of economic actors can be predicted to a large extent by assuming that they are driven by maximization of self-interest, only the short run responses of Nature can be forecast using the existing scientific knowledge base. Indeed, there is real scientific uncertainty about the long term consequences of adoption of new techniques in agriculture. The payoff that drives the play of Nature in the innovation system is also very different from that of the standard economic actors. Nature does not seek to optimize i.e. to maximize self-payoffs vis-à-vis the moves of other players, but it responds with passive actions of self-organization (or changes to itself) as dictated by universal biophysical laws to the strategies of economic players. The evolutionary response of Nature to achieve biophysical efficiency is analogous to the evolutionary behavior of economic actors trying to achieve economic efficiency. Thus, the integration of Nature in the innovation system supports the premise of Phillips and Su (2009) that evolutionary theory is relevant both biologically and metaphorically to studies of socio-technical transitions.

It must be noted that in our construct, Nature is not at all used as in the general game theoretic sense. In game theory, Nature represents a mechanism to generate uncertainty and forms the first player in any game with informational constraints. Thereafter, it does not participate in any way in a game beyond being a programmed uncertainty generator. However, in the present work, Nature or ecology refers to the 'natural environment' which participates in the game as a non-economic actor involved in the production processes. But as mentioned earlier, Nature's strategy is not governed by standard economic rationale, but by biophysical laws as responses to the strategies of other economic players, especially farmers. Nevertheless, given the complexity of the ecological system, Nature's responses constitute uncertainty for the economic actors.

3.2. Technology paradigms applied to agriculture

Within national and sectoral systems of innovation, there reign a variety of technology paradigms that Dosi (1982) defines as 'a model and a pattern of solution for selected problems based on selected principles derived from natural sciences and on selected material technologies'. As a refinement, we propose a technology paradigm to be a pathway between three types of spaces: (i) production problems; (ii) scientific principles; and (iii) solutions. To solve a set of production problems, a technology paradigm incorporates a set of scientific principles, defines a set of techniques and offers solutions through a delivery platform.

Production problems might correspond to a combination of three types of challenges: (i) lack of technological solution; (ii) multiple solutions creating the dilemma of choice of appropriate pathway; and/or (iii) partially effective existing solutions. The global supply of scientific principles is constantly increasing as the boundaries of knowledge are pushed back by scientists. The solutions to problems are therefore found as a result of continuous endeavors in multiple scientific disciplines which feed into technological solutions. At the same time, selection and adoption are incessantly carried out from this global supply through demand triggered by initial problem conditions, institutions, learning effects, returns to adoption, positive feedbacks and innovation characteristics. Eventually as multiple clusters of actors make their choices, a dominant paradigm emerges as a function of the characteristics of the innovation system (Dosi, 1982; David, 1985; Coricelli and Dosi, 1988; Arthur, 1989, 1990; Rogers, 1995).

In the economics of innovation literature, barring exceptions, the notion of a technology paradigm has only been applied to industrial innovations. In extending it to agriculture, the following distinctions and similarities are noted. Unlike in industry, typical production problems in agriculture include low yields, plant diseases and pests, and rising costs of production. Thus, agricultural production is much more influenced by environmental conditions than industrial production. However, in both, the typology of actors delivering the solutions is similar and diffusion occurs in a network of heterogeneous adopters (Possas et al., 1996). For instance, technological solutions for agriculture problems are sourced from sciences such as plant physiology, pathology and entomology. While solutions for better yields have been developed by continuous selection and breeding for best varieties; challenges like diseases, pests and nutritional problems have been tackled via synthetic fertilizers and pesticides. With the rise of biotechnology, new methods and tools issuing from the R&D efforts of public sector and private sector actors are also being used.

As an illustration, consider Fig. 1 applying our definition of a technology paradigm to GM and GR, which reveals them to be distinct paradigms. First, the challenge addressed by both was significantly different. Second, GR was triggered by advancements in traditional plant sciences, while GM emerged from developments in molecular biology and genetics as applied to traditional plant sciences. In addition, GM solutions use insights and tools from bioinformatics. Third, the two solution models differ in terms of the degree and manner of manipulation of the genetic makeup of plants. In GM, the scientific approach to solution delivery involves a 'rational design' whereby the solution developer working at the level of genes has maximum control over the process. In contrast, in GR, trial and error methods of conventional breeding offer minimum control over processes. Moreover, genetic manipulation in GM occurs in a laboratory as opposed to genetic upgradation through breeding in a natural setting in GR. Fourth, in the case of GM plants, the delivery platform is the seed alone (especially

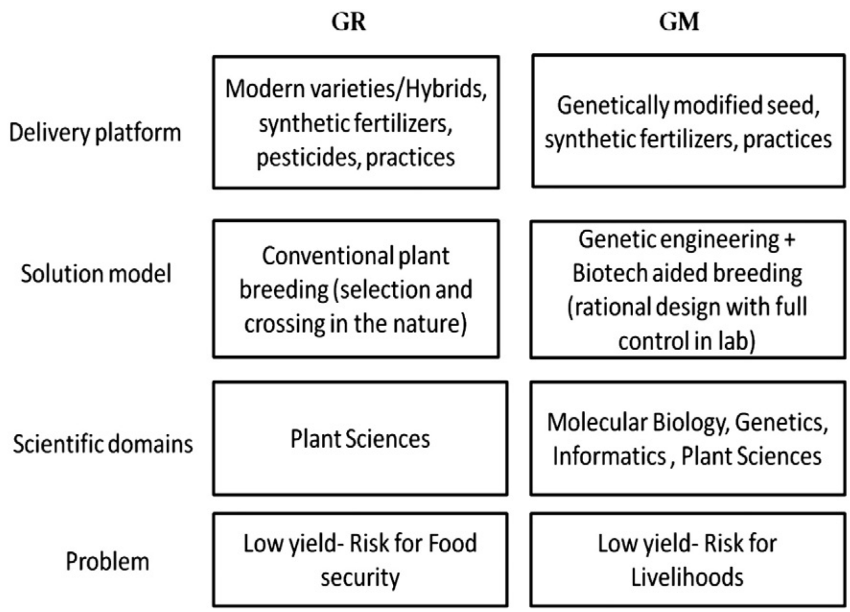

Fig. 1. GR and GM technology paradigms in Agriculture.

in the case of Bt technology); whereas, the solution in the case of GR involves additional inputs such as pesticides.

It is to be noted that a shortcoming of the notion of a technology paradigm is its generality, which permits interpretation in different ways. For instance, in contrast to Fig. 1, Parayil (1991, 1992, 2003) considers a technology paradigm solely in terms of the scientific principles supporting a solution set. He then argues that GR and GM technologies are different technological trajectories of the same technological paradigm as both the solutions utilize an overlapping set of scientific principles. Such a different interpretation stems directly from the definition used.

3.3. Technology transitions and the emergence of controversies

The process of moving from one dominant technology paradigm to another is referred to as a technology transition. Some scholars also term it as a socio-technical transition since it entails a transformation in the way that societal functions such as transportation, communication, manufacturing are fulfilled (Geels, 2002). For instance, Schot et al. (1994) analyze the dynamics of technological transition in the automobiles sector, while Kemp (1994) examines the transition towards green technologies and environmental sustainability. Technology transition has also been modeled as a process in a multi-level system, whereby niche technologies emerge facilitated by specific social groups. Thereafter, aided by pressures exerted on the existing regime by factors from the larger socio-technical landscape, they move up into existing technology regimes, kick-starting a regime shift (Geels, 2005; Geels and Schot, 2007). Though some of these studies mention that actors (social groups) trigger changes in the macro landscape, they do not examine how this happens in detail. Moreover, scant attention has been given to the emergence and influence of controversies within technology transitions.

To close these gaps, we propose a theoretical construct with the following axioms.

The movement from one dominant technology paradigm to another within the innovation system occurs as a part of three different kinds of activities: (i) technology search; (ii) technology selection; and (iii) technology diffusion as shown in Fig. 2. A new technology is conceived in the first stage as a possible response to a productivity problem. Solutions to problems are found as a result of continuous endeavors in multiple scientific disciplines. At the same time, selection and adoption are incessantly carried out from the global supply through demand triggered by initial conditions, history, institutions, learning effects, returns to adoption, innovation characteristics etc. Eventually as multiple clusters of actors make their choices, a dominant paradigm emerges. Then as it diffuses, economic and ecological impacts are generated.

Economic actors involved in technology search, selection and diffusion choose strategies to maximize payoffs as a function of their beliefs about the possible economic and ecological impact. In contrast, Nature responds to the actions of the economic players according to biophysical laws rather than economic rationality. The belief-strategy couples of economic actor groups along with their role and power in the innovation system determines the evolution of technology transitions.

Technology transitions therefore cannot be associated with any notion of consistent ‘equilibrium’ for they are the outcome of strategies of agents who rather than optimizing, continuously adapt to a shifting environment, while pursuing their goals. Consequently with such continuous evolution, the discourse cannot be in terms of static equilibrium, but only in terms of outcomes over time, which may or may not converge. Finally, these outcomes need not be socially optimal or even economically efficient at either a niche or sector level.

In common parlance, there is controversy when the beliefs of economic actors on economic and ecological impacts are not the same. However, defined in this fashion, controversies are omnipresent. Therefore, in what follows, we consider only those controversies that lead to a social dilemma, a policy dilemma or a policy failure in the innovation system. A social dilemma is an outcome that is Pareto inferior, i.e. there exists another possible outcome which yields a higher payoff to all stakeholders involved, but which is not being attained. A policy dilemma is one, where either an existing policy is flouted or a more effective policy cannot be designed. Either of these dilemmas can lead to sub-optimal societal outcomes.

Controversies may be driven by popular beliefs about an uncertain future rather than established scientific insights. Even if new information is constantly being generated in the system, it is well known that

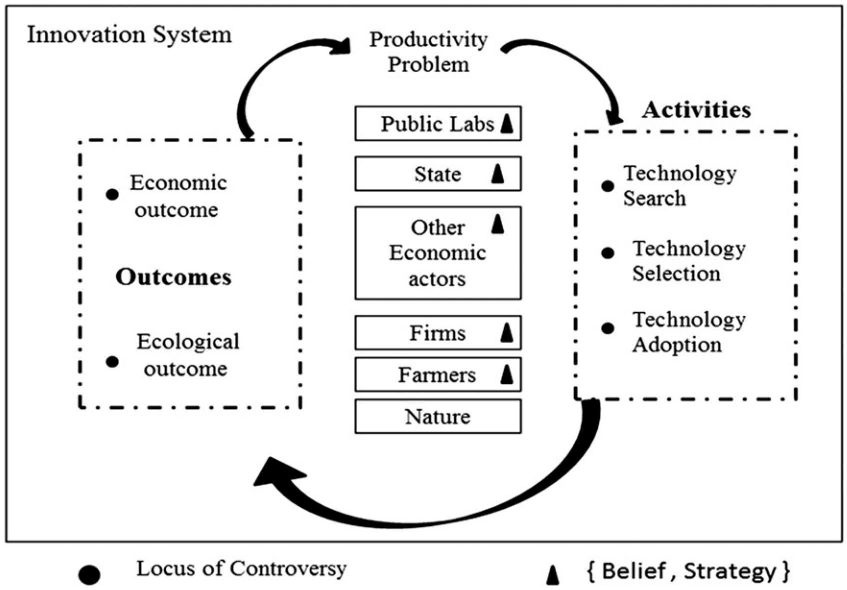

Fig. 2. Emergence of controversies in technology paradigm shifts in agriculture.

rational mechanisms like Bayesian updating can lead actors to either conform more closely to reality or further encrust false beliefs as a function of their starting beliefs and the new information accessed.

Finally, controversies can arise at any stage of the technology transition game and translate into a variety of behaviors ranging from expression of disagreement to retaliatory actions in coalitions by cluster of actors. Indeed, there could even be economic actors in the system working against the build-up of a consensus about the impact of new technology, for the resulting outcome would be less favorable to them (Henry, 2011). In the economics of innovation only social dilemmas triggered by market forces have been highlighted (Arthur, 1989; Cowan and Hulten, 1996), which may require policy intervention (Cowan and Gunby, 1996). However, in our case, significantly asymmetric belief-strategy configurations can result from confrontation of scientific and perceived uncertainty about payoffs.

To summarize, we consider a technology paradigm to be a set of three component vectors of problem, science and solution. Thereafter, shifts in technology paradigms are viewed as outcomes of actor strategies during technology search, selection, diffusion and generation of economic and ecological impact. In agriculture, technology transitions are shaped not only by the strategies of economic actors but also by the responses of Nature, which determine ecological impact. Controversies can emerge at each and all of these stages, due to differences in actor beliefs, which sometimes can lead to social dilemmas or failure of state policy. We now apply the framework to GR and GM transitions in India.

4. Analysis of Green Revolution and Bt cotton in India

In this section, we start with a historical reconstruction of the entry and diffusion of GR and GM. Then we analyze findings on the economic and ecological impacts of the two technology paradigms from multiple literature sources. Finally, we end with a survey of Bt cotton adopters.

4.1. The Green Revolution in India

4.1.1. The productivity problem

From the beginning of the 1960s, when India's population rose to about 480 million, severe food shortages began to be experienced and India began to import about 10% of its indigenous food grains production from the USA under the PL480 program (*Public Law 480*). It is widely acknowledged that the Lyndon Johnson administration was trying to use the PL480 program for political ends also, to put pressure on India to take a favorable view of the American involvement in the Vietnam War. Such was the food shortage that the Indian Prime Minister called upon his countrymen in 1964 to skip one meal a week so that others could eat (Sinha, 2001). International portrayals of India as a country with a begging bowl were far from flattering.

4.1.2. Technology search

Far away from India, Norman Borlaug, an American agricultural scientist arrived in Mexico in 1944 to join the CIMMYT (*Centro Internacional de Mejoramiento de Maiz y Trigo*) as part of a collaboration program between the Rockefeller Foundation and the agricultural ministry of Mexico. His research over the following decade led to the creation of a new semi-dwarf variety of wheat, suitable for the tropics, with 'short legs' that could support a greater amount of wheat grains on a stalk and mature early. This new variety was a radical technological breakthrough. Borlaug created it from the local Mexican varieties with the dwarfing genes sourced from a Japanese variety (Norin10). Along similar lines IR8 (or 'Miracle Rice'), a semi-dwarf rice variety was developed from its Taiwanese and Indonesian parents at IRRI (*International Rice Research Institute*) by the mid 1960s (Peng et al., 2010). The semi-dwarf varieties clearly yielded more than the conventional varieties of the time paving the way for the creation of several 'high yielding variety' (HYV) or 'modern variety' (MV) seeds which ushered in the GR.

4.1.3. Debates during the technology selection

Norman Borlaug visited India in 1963 and left 100 kg of seed of four wheat MVs developed at CIMMYT with the Rockefeller Foundation, which in turn began collaborating with the Ford Foundation to find Indian public laboratories to test these MVs in the field. In the Indian parliament, C. Subramaniam, appointed as the Minister of Agriculture in 1964 to resolve the food crisis, unfolded a two-pronged strategy: first, search for the best technology possible in the world to grow food grains; second, change the pricing policy to provide sufficient incentives for farmers to increase production. He called upon the scientists from the IARI (*Indian Agricultural Research Institute*) for advice and they in turn introduced Subramaniam to Ralph Cummings of the Rockefeller Foundation, who informed him of MVs. Then, in 1965, he went to a regional FAO conference in Manila where he met scientists from the IRRI (*International Rice Research Institute*) and learnt of MV rice varieties.

Subramaniam decided that the Indian State must pave the way for the adoption of MVs even if it meant increasing the government's expenditure significantly. This proposal provoked an outcry from all quarters: the academics within IARI, and other politicians. The communist party was paradoxically in favor of American grain imports rather than trying out the MVs, as the USSR was also importing grain from the USA. Thus, there was a lack of consensus in the parliament and among the agricultural scientists. However, the Prime Minister himself sanctioned Subramaniam to import 23,000 t of wheat seed from Mexico, of which 18,000 t was from the CIMMYT for distribution in the 1965–66 cropping season. A former director of the IARI notes "Thus began the ambitious program of producing 25 million tons of wheat, unparalleled in the history of agriculture anywhere in the world." Dr. Borlaug later said that while CIMMYT evolved the new seed, it was the decision of India to import the seed that set a chain reaction not only in India but also in Pakistan and elsewhere." (Sinha, 2001). The wheat and rice MVs were initially not diffused throughout India, but introduced in selected states best endowed with the required agro ecological conditions and irrigation infrastructure.

4.1.4. Technology adoption without controversy

In the Indian case, the triumph of the GR was not due to technology alone, but to a lining up of a favorable configuration of actors and conditions favorable to the integration of the new technology. Once the decision was taken to adopt MVs, Indian scientists worked on a mission-mode as the food insecurity crisis was perceived to be a threat to national autonomy. These scientists also played a major role in the IARCs (International Agricultural Research Centres). Much of the basic germplasm in IARCs came from Indian research institutes, the cotton MV was entirely an Indian creation and the MVs were designed to be resistant to local pests, taste good, and give high yields (Pray and Nagarajan, 2012). Evenson (2002) notes that in Asia, the contribution of the IARC network to the creation of MVs from 1965 to 1988 was greatly outweighed by those of the national agricultural research systems, in terms of investment in scientific manpower and R&D expenditures.

The State likewise greatly facilitated the diffusion of new technology by providing institutional support for credit, irrigation facilities, power, fertilizers while subsidizing MV seeds and issuing minimum support prices in the markets. In addition, a number of new supporting organizations were created for public purchase and distribution of produce. Access to farm equipment and inputs was greatly improved in the rural areas (Dorin and Landy, 2002). This reconfiguration of the innovation system was crucial to the success of the Green Revolution.

4.1.5. Evolution of the innovation system in the post-GR period and emergence of controversy over impact

The success of GR ensured strong government support for public sector research. There was little by way of offerings by the private sector. New enhanced plant varieties produced by public research institutions were transferred to national and state seed corporations, which produced the seeds for farmers. Fertilizers were supplied by the public sector companies or co-operatives. Nevertheless, within a decade of the diffusion of GR, claims that it was causing socio-economic inequality across landed and landless farmers began to be acknowledged (Frankel, 1971; Frankel, 1973). Activists claimed that GR were causing extensive resource degradation and environmental damage because of non-judicious usage of inputs such as ground water, fertilizers and pesticides (Shiva, 1989; Shiva, 1991). However, such controversies did not hinder the creation, adoption or diffusion of modern varieties in any way.

4.2. Economic liberalization and entry of Bt cotton[3]

From the late 1980s, in India, economic liberalization was introduced in a series of major reforms that allowed both foreign multinationals and large Indian conglomerates to enter the seed sector. The embrace of market capitalism coincided with the fading away of international public organizations and the rise of private firms as the major players in the Indian agricultural innovation system. The market share of private firms in the seeds markets increased dramatically. Similarly, private companies including multinationals began to dominate the pesticides and fertilizers markets. While the role of the State as a supplier in the seed markets diminished over time, the regulatory bureaucracy involved in the post-production phase of seeds was expanded and tightened through the setup of institutions and framework for seed quality evaluation and certification (Pray et al., 2001).

The enormous success of GR also engendered a winner's curse leading the Indian agricultural research system to have near-unique focus on the creation of new modern varieties to suit the different terrains of India, to the utter neglect of new fields like biotechnology till it was forced upon them. Ramaswami and Pray (2007) also point out that scientists were not used to working in multidisciplinary teams (e.g. with scientists from different branches such as agronomy, plant breeding, plant pathology, entomology and biotechnology) required for the development of transgenes for commercial use and they were not familiar with the protocols for satisfying regulatory requirements. Moreover, as part of the reform package in 1991, public spending on agricultural research was cut, lowering the incentives for innovation creation even further. On the other hand, the investment on subsidies continued far beyond the initial phase of GR diffusion, rising steadily, so that by 2005 it was around five to six times the investment in public research (Braun et al., 2005). Thus, by the beginning of the 1990s, grave productivity problems in agriculture, widely acknowledge ecological degradation coupled with market freedom ushered in by economic liberalization paved the way for leading international firms in agri-biotechnology to enter the Indian innovation system.

4.2.1. The productivity problem

By the start of the 1990s Indian cotton yields were among the lowest in world, with high cost of cultivation, poor quality seeds and poor fiber attributes of hybrids, which deteriorated rapidly with successive pickings (*Technology Mission on Cotton*, *Ministry of Agriculture*, *India*). The consumption of pesticides by cotton cultivation was as high as 54% of the total pesticide consumption in the country. This high usage of pesticides was an attempt by the farmers to save the produce from the pernicious bollworms, increasing the burden on poor farmers and severely damaging the environment (Raghuram, 2002).

4.2.2. Technology search

In 1911 in the province of Thuringia, in Germany, a scientist discovered that a commonly occurring bacterium of the region *Bacillus Thuringiensis* could act as an insecticide against the local 'flour moth'. This led to the commercialization of an insecticide using this bacterium in France in 1938 and in the USA during the 1950s. Subsequent generations of the product were marketed in the form of a bacterial spray. Around 1982, scientists at Monsanto, a leading agrochemicals company then, and a world-leader in agri-biotechnology now, succeeded in isolating the genes of the Cry family responsible for the production of the toxin in the bacteria, which is reputed to provide a high degree of resistance to major insect pests such as bollworms. Then, they inserted

[3] The details on controversy surrounding Monsanto's introduction of Bt cotton in India are also discussed in Ramani and Mukherjee (2014) S.V. Ramani, V. Mukherjee, Can breakthrough innovations serve the poor (bop) and create reputational (CSR) value? Indian case studies, Technovation, (2014). where they were used to explain firm strategies with respect to corporate social responsibility.

the gene from Bacillus Thuringiensis into crops such as cotton and corn, which came to be referred to as Bt cotton and Bt corn. This constituted a radical technological breakthrough in plant production technologies. Bt cotton is a typical example of a GM plant variety producing its own insecticide, a Bt protein-based toxin that kills the pest when it ingests the plant parts.

4.2.3. Technology selection

Monsanto commercialized Bt cotton varieties in the USA by 1996 and began to seek to introduce it in other countries. Initial attempts to get Government approval to license the technology to Indian firms were refused, as the technology fees were deemed too high (Newell, 2007). Then Monsanto approached the biggest Indian seed company Mahyco. Mahyco was established in 1964 in Maharashtra, India, by Badrinarayan R. Barwale, a respected plant scientist who was to win the prestigious World Food Prize in 1998. Mahyco applied to the DBT (*Department of Biotechnology*), an agency under the aegis of the Ministry of Science and Technology to import 100 g of Bt cotton seeds developed by Monsanto. Authorization was obtained in March 1995 and the process of crossing the American Bt cotton variety with the Indian ones began. In 1998, Monsanto obtained a 26% stake in Mahyco and it also created a joint venture, the MMB (*Mahyco Monsanto Biotech company*) in which each firm has a 50% equity holding.

4.2.4. Controversy in technology adaptation following selection

After three years, in April 1998, Mahyco got the green signal from the DBT to carry out small trials of Bt cotton, using 100 g of seeds in each trial plot. But, the company did not restrict itself to these small trials, drawing the attention of activists. Thus, in November 1998, the farmers group KRRS (*Karnataka Rajya Raitha Sangha*) burnt crops under field trials. In January, 1999, a case challenging the legality of the field trials authorized by the DBT was filed by well-known activist Vandana Shiva in the Supreme Court.

In July 2000, DBT granted permission to Mahyco to conduct large-scale field trials including seed production at 40 sites in six major cotton growing states with the results to be monitored by the DBT. Nevertheless, a year later, in June 2001, the GEAC (*Genetic Engineering Approval Committee* of the Ministry of Environment insisted that field trials of Bt cotton be extended by another year and that large-scale field trials on 100 ha be conducted again in 7 states to establish their safety. These field trials were also to be monitored by the ICAR (*Indian Council of Agricultural Research*). Thus the commercialization of Bt cotton was delayed by an additional year of field testing due to protests from activists such as Vandana Shiva, Nanjundaswamy (KRRS) and NGOs like Gene Campaign and Green Peace-India.

4.2.5. Controversy in technology adoption

While the deliberations on the safety of Bt cotton were going on, in 2001, a bollworm infestation swept through the state of Gujarat, but in some zones the cotton crop was unaffected raising suspicions. MMB filed a complaint to GEAC of industrial misconduct by a local seed firm, whereby Bt cotton seeds had been diffused and planted at a time when commercialization had not been approved in India. Navbharat Seeds, the company selling the illegal variety claimed that their hybrids were developed from insect resistant plants carefully chosen from a bollworm infested field. MMB could not press charges against Navbharat Seeds for its Bt-gene was not patent protected in India (Jayaraman, 2001a). Moreover, though GEAC immediately threatened to burn the cotton fields grown with Navbharat Seeds, nothing could be done because of farmer protests.

A year later, in March 2002, the GEAC approved the commercialization of three varieties of insect-resistant Bt cotton hybrids (Mech-12 Bt, Mech-162 Bt and Mech-184 Bt, under the brand name Bollgard®) in the central and southern cotton growing zones for the 2002–03 growing season. Authorization for commercialization was granted for the period April 2002 to March 2005 under the condition that any farmer using Bt cotton plants refuge zones with non-Bt Cotton covering at least 20% of the cultivated land. The refuge was to act as a barrier to pollen spread and prevent the development of insect resistance. Second, Mahyco had to submit the data on the field trials every year to the GEAC. In May 2005 the GEAC permitted the commercialization of six more Bt cotton hybrids of MMB for the Northern states (Jayaraman, 2000, 2001a,b, 2003; Jayaraman et al., 2005).

4.2.6. Further controversy in diffusion

There are regular reports in the media about four types of problems. First, in markets, seed quality is not being controlled. Since 2002 an illegal market for Bt cotton seeds, i.e. seeds which have not been validated by the Indian biosafety regulatory system before entering the market, has grown steadily. Demand for illegal seeds is high due to their confirmed ability to resist bollworm and their low price (Jayaraman, 2004). The market for unauthorized seeds is also supported by the development of new varieties created by local farming ingenuity and by informal social networks between farmers based on trust, though their quality is affirmed to be lower than that of the legal seeds (Morse et al., 2005). Second, a high degree of variance in returns to Bt cotton is claimed to be increasing farmer indebtedness. Third, negative externalities in the form of an increased incidence of secondary pests and resistance build-up in target pests is noted (Shiva and Jafri, 2004; Qayum and Sakkhari, 2006; Ramanjaneyulu and Kuruganti, 2006). Lastly, death of livestock through eating Bt cotton residues are reported in newspapers highlighting health risks (Parsai, 2006).

4.2.7. Moratorium on GM food crops

In 2009, Mahyco in collaboration with Monsanto applied for authorization to bring out a genetically modified vegetable variety, Bt brinjal, (*Solanum melongena* also known as eggplant) into the Indian market. However, after this was granted by GEAC, there were protests from civil society groups and anti-GM activists. In response, in 2010, the Ministry of Environment imposed an indefinite moratorium on the cultivation of Bt brinjal (M.o.E, 2010). Further, the Ministry initiated a series of public consultations and commissioned two studies to make an informed decision on the future GM crops. First, the Parliamentary Standing Committee Reports on GM Crops (Parliamentary Committee, 2012, 2014) opined that the benefits of Bt cotton had not trickled down well to poor farmers and the state actors including ministries and the regulatory body are simply not ready for future GM crops. Second, the Supreme Court appointed a 'Technical Expert Committee' to review the existing regulatory procedures for reducing the risks associated to GM crops (Technical Expert Committee, 2012). In July 2013, its final report stated that unless the gaps in India's regulatory system could be addressed, field trials of GM crops and the commercialization of Bt Brinjal was not advisable (Technical Expert Committee, 2013).

4.2.8. Lifting of moratorium on GM food crops

In 2014, a new neo-liberal government favoring further economic liberalization was elected into power in India and the new Minister of Environment proclaimed in the Parliament that GM crop research is in the national interest (PTI, 2014). Thus, in July 2014 GEAC cleared the approval of field trials for a range of food crops including rice, mustard, cotton, chickpea and brinjal (Menon, 2014).

This completes our historical reconstruction of the diffusion of GR and GM in India. The analysis also supports our theoretical construct and further refines it as follows.

Results 1: At the systemic level, controversies can be triggered in any of the stages of a technology transition.

Result 2: In particular, in the agricultural innovation system, the ecological outcomes rather than economic outcomes are likely to be stronger focal points of controversy.

Table 1
Meta-analysis of impact literature of Bt cotton in India.

Variable	Total number of articles studying the variable (% of total)	Number of articles proposing that value of variable has increased after adoption (% of total)	Number of articles proposing that value of variable has decreased after adoption (% of total)
Profit	27 (77.14%)	24 (68.57%)	3 (8.57%)
Cost of cultivation	27 (77.14%)	24 (68.57%)	3 (8.57%)
Yield	32 (91.42%)	28 (80%)	4 (11.42%)
Pesticide sprays for bollworm	12 (34.28%)	0 (0%)	12 (34.28%)
Total insecticide sprays	35 (100%)	4 (11.42%)	31 (88.57%)
	Total number of articles dealing with the externality	Number of articles proposing that externality has positive impact (% of total)	Number of articles proposing that externality has negative impact (% of total)
Generation of externalities impacting economic outcome.	35 (100%)	31 (88.57%)	4 (11.42%)
Generation of externalities impacting ecology.	3 (8.57%) [a]	2 (5.71%)	1 (2.85%)

[a] Studies using the same data have been counted as distinct data points. While most of the studies investigate the reduction in pesticide usage only 3 studies explicitly discuss or investigate the environmental or health outcomes.

4.3. Impact of GR — a brief meta-analysis

We compiled our corpus from multiple literature sources and databases.[4] Though we found many impact studies on GR based on cross sectional data, we restricted our analysis to longitudinal studies that covered both early GR (mid-1960s to mid-1980s) and late GR (after 1985) periods. Thus, our corpus included only 20 articles that explicitly analyzed the long term economic (productivity) and ecological impact of GR in the Indian context (see Table A.1 for the corpus).

While all the 20 articles reported a yield increase following GR adoption, 9 of the articles explicitly measured the evolution of the TFP (*Total Factor Productivity*) along with the increase in output over time. TFP is defined as the 'residue of effects' that account for the change in the output not caused by measurable inputs and it represents a measure of technical change. Only 3 of the 9 articles measuring TFP identified an increasing TFP over time. Indeed, the remaining 6 articles on TFP evolution reported a stagnant or decreasing growth in TFP from the mid-1980s implying that output increases were being primarily driven by increased use of inputs rather than by technological improvements thereby increasing the risk of resource degradation (see Table A.2). Evidently, under this scenario the production system is not ecologically sustainable and therefore will also not be economical in the long run (Lynam and Herdt, 1989). This is also confirmed by government figures on the aggregate yields of rice and wheat which became flatter (see Fig. A.1). While Coelli and Rao (2005) rightly point out that results of TFP studies depend on the chosen methodology, output and regions, several scholars (Byerlee and Murgai, 2001; Nagarajan, 2005; Dhillon et al., 2010) affirm that even in the high yielding regions of Haryana and Punjab, productivity increase is stuck at a plateau in both rice and wheat due to both a fatigue in the vigor of modern varieties and a degradation of resources.

In our corpus, 11 articles express concern about ecological externalities and 4 are doubtful about the impact of GR on income distribution and poverty reduction. For instance, it is noted that farmers who could adopt GR successfully were those with larger land holdings or better access to complementary inputs like water and agrochemicals (for good surveys and analysis of the impact of GR in India see Freebairn, 1995; Das, 2002; Evenson and Gollin, 2003). GR technology calls for irrigation and usage of synthetic fertilizers. However optimal usage of these inputs was not practiced by farmers in many regions (Pingali, 2012; Pingali and Rosegrant, 1994) Unsurprisingly, the literature abounds with reports of lowered ground water tables in the regions of Punjab and Haryana where GR practices were intensive (Agoramoorthy, 2008). Increased water logging due to intensive irrigation and improper drainage affects soil fertility. Also indiscriminate usage of synthetic fertilizers affects the pH value of the soil particles lowering the availability of essential nutrients for plant growth. Activists like Shiva (1989) point out that the GR intensification caused a significant loss of bio-diversity and increased the dependence of farmers on agro-chemicals, problems that the State did not address sufficiently even after the euphoria about GR had blown over.

4.4. Impact of Bt cotton — a brief meta-analysis

A similar meta-analysis was carried out on the impact of Bt cotton in India using multiple literature sources.[5] The final corpus comprised 35 articles that explicitly discussed the long term socio-economic and ecological impacts of Bt cotton in the India (see Table A.3 for the corpus).

While all 35 studies focussed on economic performance, only 3 looked into environmental outcomes along with the economic ones. This illustrates the scant attention paid by economists to the long term ecological consequences of Bt technology, which could be because it is outside their expertise and scientific uncertainty shrouds the technology. A majority of the articles measuring the changes in the profits, cost of cultivation and yields found an increase in all the three i.e. Bt cotton fetched higher yields and profits for the farmers even though its cost of cultivation rose.

While table 1 indicates only minor differences on the economic impact of Bt cotton, within the academic community debates are still ongoing on the long term consequences, as evident from recent articles by Stone (2012) and Herring (2013) taking staunchly opposing viewpoints.

[4] Our search strategy for building the literature corpus for the meta-analysis was mixed. We looked into Econlit, Econpapers, Scopus (Economics) which are standard databases, also Government reports and other research output on the impact of GR. While searching in the standard literature databases we looked for journal articles with the search string ('Green revolution' and 'India').

[5] We looked into Econlit, Econpapers and Scopus (Economics) which are standard literature databases. Also included in the search were NGO reports and regional research studies on the impact of Bt cotton in India. While searching in the standard literature databases we looked for journal articles with the search string (('Bt or Bacillus Thuringensis' or 'GM or genetically modified') and 'cotton' and 'India').

Table 2
Ranking of the reasons for continued use of Bt cotton (59 respondents).

Importance scale	Non-availability of non-Bt in the market (% of total)	Perceived higher profits (% of total)	Imitation (% of total)	Ecological reasons (% of total)
Rank 1 (most important driving factor)	0 (0%)	53 (89.83%)	2 (3.39%)	8 (13.56%)
Rank 2	5 (8.47%)	5 (8.47%)	46 (77.97%)	0 (0%)
Rank 3	6 (10.17%)	1 (1.69%)	5 (8.47%)	5 (8.47%)
Rank 4	0 (0%)	0 (0%)	1 (1.69%)	0 (0%)
Irrelevant	48 (81.36%)	0 (0%)	5 (8.47%)	46 (77.97%)

4.5. Farmer survey

In order to gain some insight on drivers of new technology adoption, we carried out a survey of 127 farmers between November 2011 and April 2012 in the states of Andhra Pradesh and Telangana. Adequate representation was ensured in sample in terms of diversity in farm resources, farmer backgrounds and agro-ecology (see Table A.4). The surveyed farmers were those who had switched to Bt cotton hybrids since it had been made available in their local markets and had continued using Bt cotton. Thus, they could compare the changes in key economic and ecological variables before and after the adoption (see Table A.5 for the final semi-structured questionnaire).

The first question to the farmers was: Why are you continuing to use Bt cotton? The farmers had to rank four options and the results are shown in Table 2.

As Table 2 indicates, there are two forces at work: perceived higher profits and a band-wagon or herding effect each reinforcing the other. The latter had also been noted by Stone et al. (Stone et al., 2014).

Second, the farmers were requested to indicate changes experienced with Bt cotton over time and their responses are presented in Table 3.

A majority of the farmers enjoyed increased profits along with increased yields even though the cost of cultivation had risen. Even within the small sample the outcomes are strikingly in line with the findings of the meta-analysis (compare Tables 1 and 3). A majority of farmers did not perceive much ecological damage from their Bt cotton experience. However, a sizable population (about 31%) think that ecological problems in terms of increased pest and disease incidence is a reality and there is a slight disagreement on parameters such as soil fertility (which cannot be directly linked to the new technology per se). This shows that even in a small sample of farmers, there is still uncertainty and disagreement on the externalities generated by the implementation of the technology.

The meta-analysis and the farmer survey thus lead to our third result that not all significant differences in beliefs evolve into controversies.

Result 3: Large scale adoption can co-exist with significant differences in beliefs on the long term economic and ecological impacts of a new technology, when short run payoffs are high.

5. Conclusion

The objective of the present paper was to analyze the anatomy and evolution of controversies that accompany technology transitions in agriculture. To this end, a theoretical construct was proposed whereby technology transitions were represented as the continuous outcomes of games played in the agriculture innovation system. Nature was integrated as an actor that responds to the production practices of economic actors in order to incorporate the ecological outcomes of technology transitions. Application of the above framework to GR and GM transitions in India, through historical reconstruction, a meta-analysis of literature and a farmer survey, yielded three further refinements.

The historical reconstruction indicated that though ex-ante it is impossible to pinpoint in which phase controversy is likely to emerge, for any radically new technology paradigm in agriculture, the controversy is likely to be centered on the responses of Nature and the resulting ecological outcomes, which in turn can affect future economic returns. The meta-analysis of the impact literature and the farmer survey proposed that large scale adoption can co-exist with significant differences in beliefs on the economic and ecological impacts of new technology. Thus, despite being punctuated by controversy, technology transitions to GR and GM were driven by standard market variables such as expected profits and accessibility. Even if negative environmental impact was discerned by some farmers, as long as they did not pose a significant risk to high short term profit, the new technology was persistently used.

Finally, the study of controversies and technology transitions in agriculture also leads to a fourth result that can hold for any sector: the greater the complexity of the innovation system in which technology transition is embedded, the higher the likelihood of controversies.

Table 3
Impact experience of Bt cotton farmers.

Economic Impact	Total number of responses	Value of variable increased after adoption (% of total)	Value of variable decreased after adoption (% of total)	Impact on variable of adoption unclear (% of total)
Profit	95 (100%)	57 (60%)	8 (8.42%)	30 (31.57%)
Cost of cultivation	95 (100%)	67 (70.52%)	25 (26.31%)	3 (3.15%)
Yield	95 (100%)	56 (58.94%)	8 (8.42%)	31 (32.63%)
Ecological impact	**Total number of responses**	**Adoption had negative impact (% of total)**	**Adoption had no impact (% of total)**	**Uncertain about impact (% of total)**
Soil fertility	84 (100%)	21 (25%)	52 (61.90%)	11 (13.10%)
Yields in adjacent fields/crops next season	84 (100%)	12 (14.29%)	64 (76.19%)	8 (9.52%)
Cattle/animal health	84 (100%)	14 (16.67%)	63 (75%)	7 (8.33%)
Health of farmers	84 (100%)	17 (20.24%)	58 (69.05%)	9 (10.71%)
Pest and disease incidence	84 (100%)	26 (30.95%)	51 60.71%)	7 (8.33%)

When GR was introduced, the creation and release of new plant varieties was controlled by a set of public agencies coordinating with one another. However, with the adoption of economic liberalization, the innovation system became more self-organized with lesser intervention from the previous dominant players. From the early GR era (late 1960s) to the Bt cotton era (from 2002) the number and variety of actors in the innovation system and the interactions between them increased (see Fig. 3). Thus, the innovation system became more complex at the time of entry of Bt cotton as compared to GR. It also became more difficult for the state to control the innovation system as the public sector laboratories had bowed out as key players, to be replaced by private firms and foreign multinationals with clearly superior technological capabilities and strategies driven by market signals. Unsurprisingly, controversies increased. However, changes in the rules of the game via regulation with respect to Bt cotton failed to eliminate controversies.

As the above discussion suggests, complexity within an innovation system increases as the number or variety of actors, actor interactions or strategic possibilities increases. With greater complexity the potential for contradictory strategic positioning of actor-communities naturally becomes greater. The likelihood of controversies in an innovation system increases with a rise in anarchy, when the degree of control (or bargaining power) of the State (whose rationality and strategy aims at a socially optimum outcome) decreases and clusters of actor-communities choose their actions on the basis of their private objectives, beliefs and information base. As the number of private players, whose rationality is to maximize own payoffs increases, the outcome may not always be a social optimum. Then to ensure co-ordination and co-operation the rules of the game have to be changed via regulation.

In the light of our results, two main recommendations can be made to reduce controversy in the Indian (and other developing countries) agricultural innovation system.

There is real scientific uncertainty about the long term ecological outcomes of transgenic crops and such uncertainty can be exploited by economic actors with vested interests to strengthen their stance on complex sciences and thereby posing a major hindrance to the building up of consensus between scientists, farmers, civil society, and policy makers in the innovation system. To lower controversy there is a need for investments in long term evaluation and an agency to monitor the environmental and biosafety of GM crops with representatives from the principal stakeholder groups in the innovation system — environmental scientists, agricultural scientists, economists, lawyers and civil society groups. This may not only decrease the uncertainty, but also minimize the ex-post allocation of valuable resources for consensus building. Also possible misallocation of resources can be minimized by having a regulation that clearly defines the financial responsibilities of the state, the seed firms and the farmers in the case of adverse events.

R&D support for the creation of new conventional varieties and non-transgenic alternatives can also be increased to ensure maximum flexibility of technology choices. In other words, not only should resources be allocated to catching up in agri biotechnology, but efforts must also be made to develop better conventional varieties and non-transgenic hybrids that can compete effectively with transgenic ones. Indeed, there has been little questioning of the larger issue of why agricultural productivity has fallen in the first place, and why transgenic crops are the best option to pursue. However, any alternative that aims to compete with varieties such as Bt cotton must be as efficient in terms of productivity and generation of revenue. This problem would indeed be a big challenge for public laboratories should they wish to accept it. But it must be explored, because in innovation studies it has been pointed out that if any pareto-superior technology paradigm (i.e. an option that is better for all actors) in the innovation system exists in a dormant state, making the switch to it will be less costly for a social planner than to kick start altogether new technology searches (Kemp and Soete, 1992).

To conclude, whenever major technology breakthroughs are shrouded in uncertainty in terms of their market impact and possible externalities generated, they can give rise to a configuration of actor-communities in the innovation system in partial or total opposition to one another. With their views and actions being supported by typical micro-drivers such as resources, capabilities, and preferences, there is room for clusters of economic actors to express contradictory opinions, each fabricating its own vision of uncertainty. In such contexts, controversies can mark technology transitions, which evolve as an outcome of bargaining between actor-communities.

Acknowledgments

We thank the Editor and the anonymous referee for their insightful remarks. We thank and acknowledge the collaboration of Samira Rousseliere and Marion Menetrier on earlier versions of the paper. We are also very grateful to Eric Gall, Nico Rasters, Carl Pray, Peter Phillips, Richard Nelson and Peter Atkinson for their useful comments. We gratefully acknowledge help from G Pakki Reddy for institutional support during the survey.

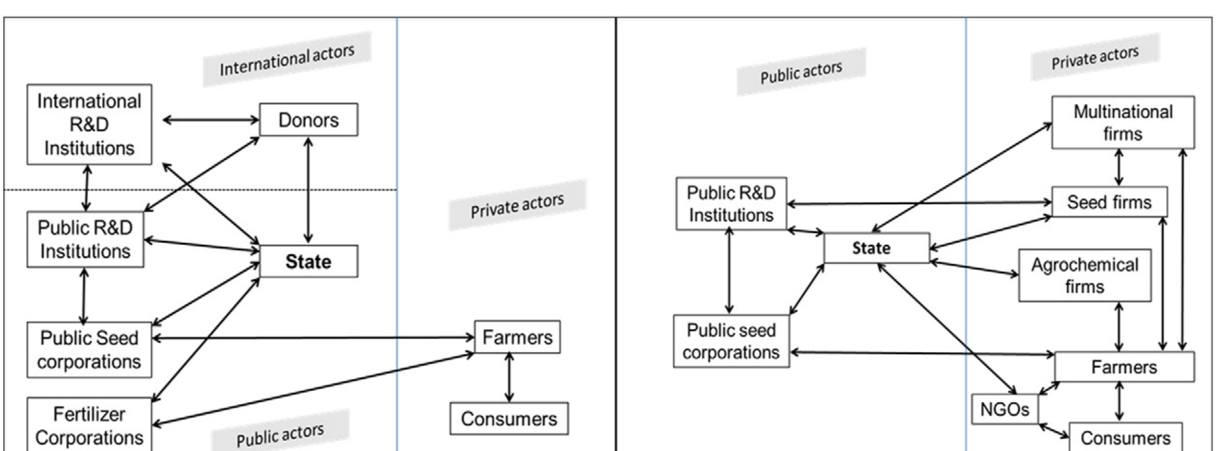

Fig. 3. Agricultural Innovation systems in India during the GR (left) and Bt cotton (right) technology transitions.

Appendix A

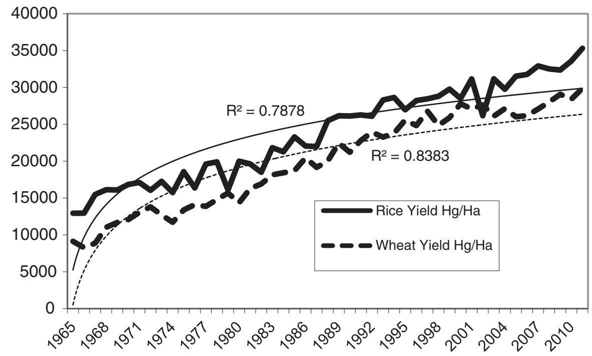

Fig. A.1. Plateauing of Rice and Wheat yield in India (with a logarithmic trend line) (*FAOStat* Database).

Table A.1
Literature corpus on impact of Green Revolution in India used for meta-analysis.

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Table A.2
Studies indicating stagnant or declining TFP growth or output growth in late green revolution period (after 1985).

Authors/year	Regions studied	Agricultural output	Years	Major findings
Murgai et al. (2001)	Punjab regions of India and Pakistan	Rice and Wheat	1966–1994	Input growth accounted for most of the output growth in Punjab. TFP growth negative in post-GR era (1986–1994) in Indian Punjab.
Mukherjee and Kuroda, 2003	14 major states in India	30 major crops and 3 livestock products	1973–1993	Negative TFP growth in Andhra Pradesh, Bihar, Rajasthan and Tamil Nadu between 1989–1993
Kumar and Jha (2005)	11 major states in India	Rice	1971–1991	Negative TFP growth between 1971–91 in Haryana, Bihar and Madhya Pradesh
Janaiah et al. (2006)	9 major states in India	Rice	1970–2003	Yield growth slowed down in irrigated regions in late GR (post 1985). TFP growth declined rapidly between early and late GR periods in Punjab and Karnataka.
Kumar and Mittal (2006)	16 major states in India	Rice, wheat, coarse cereals, oil seeds and pulses	1971–2000	Diminishing returns to input use and stagnated or negative TFP growth in late-GR.
Bhalla and Singh (2010)	17 major states in India- District level study	44 crops	1990–93 to 2000–03	Deceleration in yield growth and total output growth.

Table A.3
Literature corpus on impact of Bt cotton in India used for meta-analysis.

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Table A.4
Bt cotton farmer survey — sampling regions.

No. of sub-districts (Mandals); number of villages	District, state, country	Agro-ecological (cotton specific) classification of the survey region
11; 13	Warangal, Telangana, India	North Telangana
2; 3	Adilabad, Telangana, India	North Telangana
1; 3	Kurnool, Andhra Pradesh, India	Rayala Seema
1; 9	Nellore, Andhra Pradesh, India	Coastal Andhra

Table A.5
Bt cotton farmers' questionnaire.

Questionnaire for Bt cotton farmers in India

Personal information of the interviewee

Name:	Village:	Mandal:
District:	Phone:	Date:

1. Reason for choosing Bt cotton every season.
   Please rank the following alternatives as follows: Rank 1 for most important reason, Rank 2 for less important reason, Rank 3 for even less important reason and so on, 0 if not relevant at all.
   1. Non availability of conventional cotton hybrids in the market ☐
   2. Increased economic gains (increased yield, reduction in pesticide usage) ☐
   3. Because majority of farmers are planting Bt cotton ☐
   4. Ecological reasons (decrease pesticide usage and health problems due to pesticide spray) ☐

2. Answer the following question from your personal experience with Bt cotton
   When compared to conventional hybrids what is your experience with Bt cotton in?
   1. Yields ☐
      a. Significant increase b. increase c. reduction d. great reduction e. No change
   2. Cost of cultivation ☐
      a. Significant increase b. increase c. reduction d. great reduction e. No change
   3. Profit ☐
      a. Significant increase b. increase c. reduction d. great reduction e. No change

3. Answer the following from your personal experience with Bt cotton
   The impact of Bt cotton on the following:
   1. Soil fertility: damage ☐ no damage ☐ can't say ☐
   2. Yield of adjacent fields/Crops next season: damage ☐ no damage ☐ can't say ☐
   3. Health of Cattle/animals (consuming Bt cotton residues): damage ☐ no damage ☐ can't say ☐
   4. Health of cotton oil consumers: damage ☐ no damage ☐ can't say ☐
   5. Health of farmers: damage ☐ no damage ☐ can't say ☐
   6. Pest and Disease infestation: damage ☐ no damage ☐ can't say ☐

4. Qualitative feedback from Bt cotton experience
   a. What is the most important cotton-pest / disease problem you are currently facing ... ...
   b. Views on Regulation of Bt cotton (seed quality and refuge)…………………………………………………
   c. On extension services for Bt cotton ………………………………………………………………………………………..
   d. What is your learning if any from the experience of Bt cotton…………………………………………….

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