

Technology paradigm shifts and sustainability: an application to agricultural production

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Abstract

Major technological transitions in the history of agricultural production came about in the form of green revolution (GR) modern varieties and transgenic crops (GM crops). While the transition to GR increased the overall productivity of the sector across nations it is also seen as causing resource degradation in countries like India partly due to the technology package itself and partly due to unsustainable implementation of the same. On the other hand, genetically modified plant varieties entail uncertainty about the long term health and environmental outcomes. The understanding of dynamics of technological transitions towards sustainability pertinent to agricultural production therefore needs special attention. This article contributes to the economics of innovation literature in the following way. First, it offers a novel conceptualization of the underlying concepts of technology transitions or paradigm shifts towards sustainability. The existing ideas on the emergence and selection of technology paradigms in the systems of innovation literature are refined keeping in view the nuances of agricultural production. Second, it substantiates the conceptualization of technological transitions by empirical investigation of two major technological transitions, the green revolution in cereals and genetically modified cotton in India.

Keywords: Technology paradigm shifts, Transition dynamics, Agriculture, Sustainability

JEL Codes: O13, O31, O33, Q15

1. Introduction

The classical work of Malthus (1798) predicted that population growth will cause major food shortage, given the diminishing returns to capital and labour in agricultural production. In contrast, Boserup (1965, 1981) in her works on agricultural development argued that food production adjusts itself to the growing population pressure. The role of human endeavor to circumvent problems of population growth and falling agricultural productivity through technological efforts was indeed unperceivable in Malthusian times (Simon, 1998). It is now common knowledge that technological change in agriculture has improved the agricultural productivity in many countries by several folds (Ruttan, 2000). Though food security is still an unresolved problem, societal chaos did not occur in a majority of countries, thanks to the technical change in the sector and the international diffusion of innovations.

Major technological transition in the history of agriculture came about in the form of green revolution (GR) modern varieties and transgenic crops (genetically modified crops or GM crops). While the transition to GR increased the overall productivity of the sector it is also argued to be causing resource degradation in countries like India partly due to the technological solutions and partly due to unsustainable practices of farmers. At the same time, while the transition to agricultural biotechnology punctuated by the diffusion of genetically modified plant varieties is seen as a hope by many, there is still division of opinion on the long term health and environmental impact of this paradigm. Therefore the dynamics of technological transitions or paradigm shifts pertinent to agricultural production need special attention in view of growing concerns about sustainability.

This article contributes to economics of innovation literature in the following ways. First, it offers a new conceptualization of the underlying concepts of technological transitions in the systems of innovation literature. The existing ideas on the emergence and selection of technology paradigms and the dynamics of the system as a whole are refined keeping in view the nuances of agricultural production. The novel conceptualization succinctly captures the technology transition process from a technology development perspective while delineating the complexities such as market dynamics and actor strategies. Moreover, it explicitly integrates the evolution of 'problems' which so far has received little attention in the technology transitions literature. Second, it applies the framework to classify the major technological paradigms that marked agricultural production, and substantiates it further by an empirical analysis of two major technological transitions the green revolution in cereals and genetically modified cotton in India.

The article is organized as follows. Section 2 introduces the analytical framework by drawing from the existing literature on systems of innovation thinking. Section 3 fits the framework to agricultural production. Section 4 validates the conceptualization by the empirical analysis of the two major technological transitions, green revolution and genetically modified cotton in India. Finally Section 5 concludes.

2. Technology paradigms and Technology transitions - towards an analytical framework

Traditional models that explain the mechanism and sources of agricultural innovation are linear. The linear model suggests that innovations flow from international research centers to national research facilities, then reaching the farmers via extension. This explanation is not completely incorrect as it happened so during the green revolution period in several developing countries. However the validity of this linear model in modern day agriculture is under question for the following reasons. First, the emergence of the private sector dominance in the agricultural research and development and second the major changes to the institutions of intellectual property rights (UPOV¹) that dictate the flow of knowledge. The alternative views to the linear model that evolved over the years include National Agricultural Research Systems (NARS) with a focus of co-ordination between universities and research organizations, Agricultural Knowledge and Information systems (AKIS) and more recently the National Agricultural Innovation Systems (Worldbank, 2006)

Biggs (2007) argues that in order to achieve significant reduction in farmers' vulnerability there is need to replace the existing linear models of agricultural innovation with agricultural innovation systems that allows for interactive learning and active participation of framers and important non-state actors in agricultural innovation process. A dynamic actor innovation system framework is proposed in lieu of the linear model by several scholars (Hall, Dijkman, & Sulaiman, 2010; Spielman, Ekboir, & Davis, 2009). While arguing in favor of systems approach these scholars also add the dimension of capacity development.

Having come thus far it is important to ascertain that the application of innovation systems framework resolves three basic nuisances in enhancing the innovation generation and diffusion. They are the role of co-ordination and information/knowledge flow in the overall performance (measurable outcomes). In innovation systems, co-ordination is one of the key issues brought on board for discussion. Co-ordination involves discussions on public-private partnership, international co-operation, university-industry collaboration, and active non-state actor participation. Dealing with co-ordination failure may involve setting the rules of the game (incentives) right. Second, information flow in the system can be enhanced by dealing with the bottle necks and blockages by applying the actor-network² approach. Such an analytical framework is critical to understand the developing countries' problems of information asymmetries and co-ordination failure in agricultural innovation.

Systems of innovation thinking can be traced back to the 1990s (Freeman, 1995; Nelson, 1993) when it emerged as a strong alternative to linear models of innovation³. A network of organizations and actors focused on bringing out new products, processes and new forms of organization (innovations) into social and economic use, together with the institutions and policies that affect their behaviour and performance is generally termed as an 'innovation system'. How then is the 'innovation systems' approach different from traditional approaches?

1 The International Union for the Protection of New Varieties of Plants (UPOV) is an international convention of plant variety that protects plant breeders' rights.

2 Actor-network approach helps identify the relationships and interactions between actors' and the role of key actors (for instance, State) in setting the rules of the game. At the same time it is important to identify that actor-networks are, in real-time, self-organizing and endogenous given the changing set of rules that govern the system

3 Here innovation is understood as, 'a particular invention in the technological or organizational space that is socially acceptable and commercially successful'.

Innovation systems approach focuses on the research and development processes by taking stock of the key stake holders as well as the rules of the game (regulation and policies) that determine their play in a national, regional or sectoral context (Lundvall, 1992; Malerba, 2002; Nelson, 1993). While it is true that the systems approach simplifies the representation of the complex world it is nevertheless a straight forward way to deal with the co-ordination, efficiency and other functional problems at a system level.

The ‘system’ that typifies the process of innovation generation and diffusion is portrayed in diverse ways by economics of innovation scholars. While some of the ways are centered on the technological artifacts, organizations and related materials (Hughes, 1987), others are centered on the artifacts as well as the underlying economic system (network of actors) within a sectoral or geographical context (Carlsson & Stankiewicz, 1991; Lundvall, 1992; Malerba, 2002, 2004; Nelson, 1993). Table 1 shows the conceptualizations that broadly typify the systems of innovation.

Table 1 Evolution of systems of innovation concepts

Author/s (Year)	Notion	Representation
Hughes (1987)	Large Technological systems	Physical artifacts (machines, tools etc) and Organizations constructed and being shaped by societies.
Carlsson and Stankiewicz (1991)	Technological systems	Network of agents interacting in a particular technology area exchanging knowledge and competencies.
Lundvall (1992); Nelson (1993)	National Systems of Innovation	The structure comprising economic actors who are responsible for the creation, development, diffusion and adoption of innovations within a country.
Malerba (2002, 2004)	Sectoral systems of innovation	System comprising of Knowledge and technology, actors and networks, and institutions specific to a sector.
Geels (2004, 2005); Geels and Kemp (2007)	Socio-technical systems	Clusters of elements involving technology, science, regulation, user practices, markets, cultural meaning, infrastructure, and production and supply networks.

At this juncture it is important to distinguish the three basic building blocks of the systems of innovation approach. First is the actor networks, second, the tangible technical and non-technical artifacts and third, a variety of intangible elements such as rules, actions, functions etc. Analyses can focus on each or all of these elements to solve a functional or change management problem. That is, from an analytical perspective, ‘systems of innovation’ approach also provides scope for analyzing the functional as well as the change aspects of the system (Geels & Kemp, 2007). Functional exploration involves studying the basic construct, functioning of individual modules (individual actor behaviour) and systemic cohesion (actor interactions and input/output) for achieving desired outcomes. Examining the change aspects of the innovation system includes understanding the internal and external processes that drive the larger

technological evolution of the system (emergence, stability and collapse of the systemic structures etc).

In this regard, the application of evolutionary principles (Nelson & Winter, 1982) contributed significantly towards the general understanding of technical change from both functional and change perspectives. In this school of thought, the dynamics of firm (or actor) behaviour and market outcomes are explained in terms of biological evolution. The rule-based ‘routines’ that determine a firms’ behaviour are akin to the behaviour of ‘genes’ in a biological setting with a possible ‘mutation’, that is, a noteworthy change in the ‘routines’. This mutation can potentially create a new species, biologically, or a new search routine, metaphorically (Nelson & Winter in the *introduction* of the book *An Evolutionary Theory of Economic Change*). These concepts are powerful tools to understand the construct, function and evolution of economic systems.

Within this broader framework of evolutionary dynamics, Nelson and Winter (1982) introduce the notion of technological regimes referring to the similarities in the organization of the search heuristics that dominate the actor (engineers and scientists) behaviour in an innovation system. Here the technological evolution is characterized by regimes and trajectories. A regime specifies a dominant pattern of behaviour that the actors follow to come about with solutions to problems. Their behaviour, for instance, in searching for technological solutions, is based on established ‘cognitive routines’ or ‘heuristics’ (which are rule-based) that push a ‘technological trajectory’ in a particular direction. Here technological evolution is explained in terms variation and selection. While ‘variation’ refers to emergence of a variety of search routines, ‘selection’ determines their fate. Selection here is akin to ‘natural selection’ in the biological evolution where the ‘survival of the fittest’ rules the system. Selection mechanism ensures that only those search routines that are proven to be profitable stay put and survive in the system while others get killed.⁴ Further, the innovation system is characterized by simultaneous search and selection processes that not only influence the direction of technological evolution but also lead to the rise and fall of economic actors as both winners and losers both reconcile their search routines.

At around the same time, Dosi (1982) proposed the notion of ‘technology paradigms’ and characterized the change processes within the technology paradigms as ‘trajectories’. Here, technological evolution is explained from the perspective of changes to the supply and demand of technologies. Later on Sahal (1985) argued that technological evolution is dictated by chance and necessity and is guided through innovation avenues by technological guide posts. Perez (2004, 2009) explains the technological evolution and paradigm shifts in terms of radical and incremental innovations. Here technological evolution is dictated by emergence of radical innovations (revolutions) and is shaped by the incremental innovations that are developed by means of technological efforts in the same direction as that of the radical innovation. Also technological evolution is explained by the entry of niche innovations into existing regime drawing from the ideas of sociology of technology (Rip & Kemp, 1998) and during the later years in a multi-level systemic perspective (Geels, 2002).

Table 2 Concepts that typify technological evolution

⁴ The selection mechanism is still the most important postulation that drives and holds together the neo-Schumpeterian view of economic dynamics.

Author/s (Year)	Concepts
Nelson and Winter (1982)	Technological regimes and Trajectories
Dosi (1982)	Technological paradigms and Trajectories
Sahal (1985)	Technological guide posts and innovation avenues
Kemp <i>et al</i> (1998), Rip and Kemp (1998)	Niches and Regime shifts
Perez (2004, 2009)	Technological revolutions and Paradigm shifts
Geels (2002, 2004, 2007)	Technological transitions in a multi-level perspective and transition pathways

As Table 2 indicates although the terminology varies all these scholars were interested in the rise and fall of major technological domains, the evolution of technological solutions in those domains and their societal or economic implications.

For a given problem context, a technological paradigm shift or technological transition⁵ can be seen as a systemic shift from one dominant paradigm to another. As a paradigm shift entails changes to societal as well as technological configurations these can also be seen as ‘socio-technical transitions’. In the tradition of socio-technical transitions Kemp *et al.* (1998) and Geels (2005; 2004; 2002) elucidated the transition dynamics in the technology regimes from the perspective of niche innovations. From a multi-level perspective introduced by Geels (2002) innovations from the niche region (level 0) enter into the existing regimes (level 1) that are opened up by pressures exerted by the changes external to the regime, that is, from the socio-technical landscape (level 2). Further, the change processes as well as the typology of transition pathways are explained using the multi-level perspective (Geels & Schot, 2007; Geels & Kemp, 2007)⁶.

In an empirical convention, the works of Kemp and Soete (1992), and Kemp (1994) for the first time study technology transitions towards environmental sustainability. During the later years more empirical efforts were made to throw light on the dynamics of technology transitions, particularly on transition towards sustainable technologies. In this regard, while Kemp (1998; 1994) study the transition towards green technologies and sustainable waste management, Schot *et al* (1994) study the transition to electrical vehicles. Though several of the empirical analyses of technology transitions focus on societal functions such as factory production, transportation, communication, energy, a robust theoretical base to explain the transitions from the particular view point of agricultural production are limited in the broader area of innovation studies.

2.1. Technology paradigms and the global technological landscape

⁵ Technology paradigm shifts and Technology Transitions are used interchangeably in this thesis.

⁶ Geels and Kemp (2007) distinguish the change processes as Reproduction, Transformation and Transition. Geels and Schot (2007) typify the transition pathways as Transformation, De-alignment and Re-alignment, Technological Substitution

Before dwelling into the discussion on the emergence of technology paradigms it is important to first understand what constitutes a technology paradigm and what constitutes a paradigm shift. Dosi (1982) defines a technological paradigm as “a model and a pattern of solution for selected problems based on selected principles derived from natural sciences and on selected material technologies”. He defines technological trajectory as “a pattern of normal problem solving activity on the grounds of such a technological paradigm”. Though this is a very broad notation for what constitutes a complex technological domain it throws out four basic elements useful for characterizing a technology paradigm. They are: the problems, the principle areas of scientific enquiry, the dominant solution model (or pattern of solution development), and the solution package (or the platform of solution delivery). Technological solutions, therefore, can be placed under the umbrella of paradigms which emerge, evolve, (occasionally co-exist) over time and those which differ in terms of the problems being addressed, the selected principle scientific fields and their dominant solution designs, and platforms of solution delivery (materials and technologies).

Keeping in mind these basic elements of a technology paradigm we now attempt to refine this general notation. First we start with the problem set. Consider a set of technological challenges in production. There can be Z problems that denote the production challenges at a given point of time.

Let the problem space be $W = \{1, 2, \dots, p, z, \dots, Z\}$

Let $T = \{t_1, t_2, \dots, t_i, \dots, t_n\}$ be the set of all existing technological solutions for the problems in W .

Let $S = \{s_1, s_2, \dots, s_i, \dots, s_n\}$ be a given set of scientific fields in which solutions for the set of problems in W could be searched for.

Let us consider a problem p from the set W . Now for such a representative problem p , let there be n possible technological solutions given by the set $T_p = \{t_{p1}, t_{p2}, \dots, t_{pi}, \dots, t_{pn}\}$. This can be an empty set if there are no available technology solutions at a given point of time. For simplicity, we only focus on problems for which the set T_p is non-empty.

Furthermore, any technological solution t_{pi} could be founded on m possible scientific fields; out of which let s_{pi} be one principal scientific field in $S_p = \{s_{p1}, s_{p2}, \dots, s_{pi}, \dots, s_{pm}\}$ where the set S_p refers to the m possible scientific fields that support the underlying technological solution t_{pi} . This means for a problem p in the problem space there can be n corresponding technological solutions, based on one of m possible scientific fields while based principally on a particular scientific field.

Let the tuple (t_{pi}, s_{pi}) represent one possible technological solution t_{pi} and the principal scientific field s_{pi} supporting it.

Now in the same spirit as Dosi, we specify a technology paradigm as a set of ‘technological solution’ triplets of a set of problems, their viable solutions and a set of scientific fields (along with a dominant solution design) on which the solutions are principally based on.

This construct is easy to interpret from a technology development perspective. As a dominant solution design emerges within a new scientific discipline and co-evolves with it, for simplicity, the space of scientific domains is also taken as representative of its dominant solution design which is dropped in our conceptualization.

Thus, we represent a technology paradigm by G_w such that:

$$G_w = \{w, T_w, S_w\} \text{ where } w \in W; T_w \in T; S_w \in S$$

In other words a **technology paradigm** G_w is a set of points in the 3D space representing a subset of problems w in a problem space W , a set of technology solutions T_w for those problems which are based on a set of principal scientific fields S_w which is a sub set of all available scientific fields, S .

With this definition of a technology paradigm G_w , we can now go on to describe a technology landscape.

Let L_p be the **technology landscape**⁷ corresponding to a given problem set p be a plane of all possible viable technological solutions and the principal scientific fields corresponding to the problem set p . Here the problems are closely related to each other. This means that a technology landscape corresponding to a given closely related problems set p is given by $L_p = \{(t_{pi}, s_{pi}) \in R^2\}$ where $t_{pi} \in T_p$; $s_{pi} \in S_p$.

That is, a technological solution t_{pi} and the principle scientific field s_{pi} for a problem p_i is the basic entity (building block) of a technology landscape. Here the technological solution can also be seen as solving ‘a particular problem’ of a larger problem hierarchy. That is, if a problem solving procedure (algorithm) encompasses multiple independent steps the tuple (t_{pi}, s_{pi}) represents the solution and the underlying principle scientific field that the solution is based on.⁸

Finally, the **global technological landscape** is understood as the set of all production problems at a point of time, along with their technological solutions and the principal scientific fields that the solutions are based on. In other words, a global technological landscape is also a set of all possible technology paradigms existing at any point of time.

⁷ Our conceptualization of technology landscape is different from the ‘socio-technical landscape’ of Rip and Kemp (1998) and Geels (2007) in which it represents the tangible structures and elements (such as infrastructure) that act as ‘gradients of force’ that bring about changes at the regime level. The term is used in a more general and metaphorical way to represent a ‘binding structure’ of related technology and science tuples.

⁸ For example, the problem of producing a GM plant variety involves two steps: 1. Extraction of the source gene and 2. Transfer of the gene. The solution to extracting the source gene is done by ‘molecular markers’ (let’s say A) developed using principles of molecular biology, and gene transfer is accomplished using a particular genetic engineering tool let’s say a ‘gene gun’ (Let’s say B). Then the tuple will be (A, molecular biology) for problem 1 and (B, genetic engineering). The technological solution t_{pi} could be a ‘tool’ or a ‘method’.

To illustrate these concepts in Figures 1 and 2 we designate on X-axis, the problems, on the Z-axis all possible solutions and on the Y-axis all scientific fields. Since we are representing a three dimensional space the ‘balls’ represents the ‘technology solution triplet’ i.e., a specific problem, a corresponding technological solution and the principal scientific field on which the solution is based. A global technological landscape therefore is a universal set of all ‘technology solution triplets’ and all existing ‘technological paradigms’.

A technology paradigm in this context can be seen as a construct encompassing the triplet sets (‘balls’ as in Figures 1 and 2) for a set of related problems with solutions derived from a common set of scientific principles (that follow a dominant solution design).

Similarly a technological trajectory within a paradigm is seen as the movement in the planar configurations of technological landscapes for a particular problem set based on a set of scientific fields that characterize the technology paradigm.

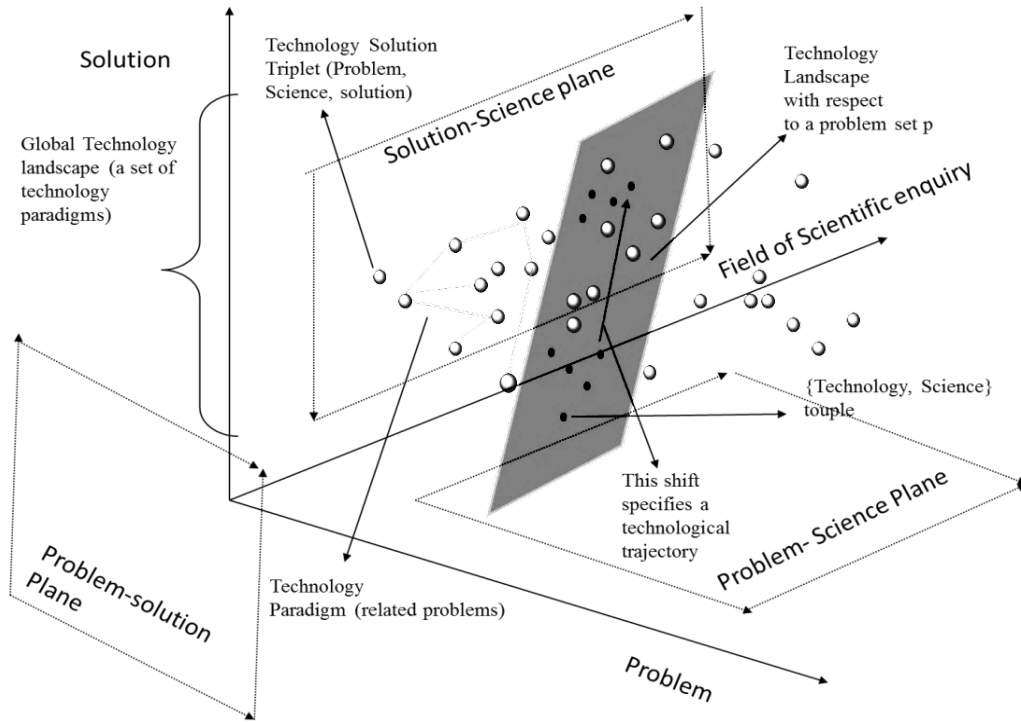


Figure 1 Global technological landscape

For a problem p_i , there may or may not be a solution available on L_p for a given problem in a given point of time. However a problem p_i needs a solution, therefore a technological search starts within the sciences that represent a dominant technology landscape T_p (suppose the only existing) for a related problem set. That is, while the search occurs within the landscape’s areas of scientific enquiry, scientists and engineers apply techniques pertinent to the dominant solution models of the landscape. If a solution is not found within an existing landscape then the search extends to other areas of scientific enquiry outside the scope of the landscape but with the paradigm’s boundary. If a solution is found in scientific areas external to the landscape but

within the paradigm then new landscapes may emerge. Gradually the paradigm extends in the direction of the trajectory of the landscapes.

Though this conceptualization of global technological landscape, technology paradigms is simplistic, it succinctly captures the transition mechanism from a technology development perspective while delineating the complexities of market dynamics and actor strategies. Moreover, it explicitly integrates the evolution of ‘problems’ into the transition dynamics which so far has received little attention in the technology transitions literature.

2.2. Emergence and Selection

Once an efficient and radical innovation emerges out as a consequence of ‘variation’, the emergence of a paradigm can be seen as the development of a set of incremental innovations over and top of that radical innovation. The evolution of a technology paradigm can be explained by the push-pull dynamics in the economic system i.e., the science-push and demand-pull of the markets (Dosi, 1988). Here scientific fields of enquiry are seen as purely supply driven and are highly dependent on the existing knowledge base. Any major development here increases the possibility of emergence of a new paradigm. On the other hand, the market demand determines the diffusion of individual technologies. The market success of innovations dictates that the suppliers of innovations invest in incremental technologies based on existing ones while unsuccessful innovations eventually die out and technological progress proceeds in that direction.

As pointed out earlier, selection is central to the evolutionary explanation of economic dynamics. There is a selection mechanism prevalent in an innovation system such that for each configuration of a set of problems, through the actions and interactions of the actors and certain system dynamics (explained later), a dominant technology emerges over time. Its success in turn opens the door for scores of incremental innovations on top it making a complete paradigm emerge over time. Selection is therefore deathlike and godly at the same time, depending on the perspective one takes. It will rid the system of inefficient technologies and sets the stage for new and economically efficient technologies. Selection is therefore a perpetual process that influences the cycle of birth, stability and death of paradigms within a global technological landscape.

Historical events and path dependence (David, 1985) are useful arguments to comprehend the stability (or inertia) of technologies within an emergent paradigm. Dominance can also lead to situation called ‘lock-in’ (Arthur, 1989, 1990; Cowan, 1990; Cowan & Gunby, 1996) where in an efficient technology gets killed while competing with an inefficient one due to increasing returns to adoption, positive feedbacks and network externalities. Increasing returns and path dependence reinforce the strength of a dominant technology and in turn the inertia of the technology landscape. This makes the paradigm shift difficult for that particular set of problems. The same forces also prevent the transition towards sustainable technologies. Explicit policy intervention that can create niches might be necessary to break the lock-in (Cowan, 1996).

2.3. Response

Agricultural production is dissimilar to factory production where the production takes

place on a factory shop floor as opposed to a natural environment. In other words, in factory production the production activity occurs in a controlled environment where interactions with the natural ecology are bare minimum. Even if the factory production causes ecological externalities, let's say in the form of water and atmospheric pollution, since the ecological parameters are not part of production, the impact on the productivity (via quality of inputs) is negligible. Therefore agricultural production by and large is characterized⁹ by *a response function* of the ecology that determines the quality of inputs thereby affecting the final outcome.

The construct and nature of a response function is understandably complex, nonetheless, the recognition of such a response function and its role in the transition dynamics is important. 'Nature' (or 'Ecology') therefore is a non-economic actor in the innovation system whose responses are strategic as its actions are governed by universal bi-physical rules. The payoff function for Ecology is constituent of attaining a bio-physical equilibrium. At the same time, Nature's response to intervention (human and technological intervention) is an outcome of bio-physical evolutionary processes.¹⁰ As the conceptualization of such non-market dynamics in the emergence and evolution of technology paradigms is hard to find in the literature they are integrated to explain the transition dynamics.

Let F be the response function of Nature such that the inputs for the function are a set of problems $p(t)$ in time period t and the technology landscape T_p cutting through the dominant paradigm G_w . The output is a new set of problems $p(t+1)$ in time $t+1$ with a probability β . That is

$$p(t+1) = F(p(t), T_p)$$

Where $p(t+1)$ belongs to $\{P; 0 \leq P \leq n\}$; n is finite; and $p(t+1)$ a set of problems that might severely undermine the future production.

That is, the emergence of a sub-optimal paradigm¹¹ (ecologically sub-optimal) as the dominant one triggers a response function by the ecology which with a certain probability poses new challenges in the form of new problems (or hitherto unknown problems) or problems that undermine the production itself. That is, ecological response can undermine the economic efficiency of the system. Therefore the sustainability potential of technology paradigms in agriculture should be analyzed in terms of both a. economic efficiency of the underlying technical change and b. negative ecological externalities caused by the technology which affect the long term sustainability of the production system.

⁹ Exception includes agricultural production in a controlled environment such as green houses.

¹⁰ For further clarity let us take two examples, 1. Usage of pesticides usually kick starts a natural biological response (changes to the DNA of target insect) thereby making it resistant to the pesticide in the long run. 2. The green revolution package of high yielding plant varieties and synthetic fertilizers. Under conditions of imperfect or incomplete information, or dilemma of inter temporal utility optimization (that often stems from the incomplete information) or any other factor that leads to non-optimizing behaviour, the farmers end up using higher levels of inputs. This in turn triggers a range of problems that include soil fertility loss, increase in salinity, water logging and fertilizer residues in soil harming useful soil bacterium, earth worms and other useful biological entities, pesticide residues in the produce and in the air (at times indirectly increasing the green-house gas emissions).

¹¹ It is important to note that a dominant solution may be efficient if implemented under conditions of perfect and complete information and rationality of full optimization.

In order to mitigate the problems that undermine the production process that emanate due to sub-optimal technologies (or their implementation) switching to an efficient technological solution by the way of technological search process in the same technology landscape becomes necessary. Once the economic actors in the innovation system perceive this inevitability the evolution of the paradigm or a trajectory within the paradigm is kick-started. If the solution is not found in the existing landscape then the technological search extends to other scientific disciplines that constitute the dominant paradigm.

2.4. Transition or paradigm shift

The most efficient way of delivering the solution to the problem may or may not be found in a dominant paradigm. In this case the search may extend into a non-dominant or dormant technology paradigm which co-exists with a dominant paradigm. Although exploration of the origins for such co-existence is indispensable, the co-existence can be taken as given at this juncture as there is enough evidence to believe that such dormant paradigms constituting less efficient(economically), local knowledge centric or culture centric, or appropriate (Schumacher, 2011) emerge over time.¹² Examples include agro-ecological paradigm in agriculture which is based on traditional knowledge (nutrition and pest management through locally available biological resources), and the paradigm of alternate medicine (Traditional medicines, Homeopathy, Acupuncture etc) for health ailments. The dynamics of such a dormant paradigm may or may not be explained by the standard interpretations.

If a more efficient solution is found in a dormant paradigm, switching is less costly than kick starting an all new technology search process (Kemp & Soete, 1992). This simply means that if a solution from a dominant paradigm causes negative ecological externalities (non-market)¹³ then switching to another solution which is efficient could be envisaged by the actions of the economic actors. This may not be possible given the evolutionary forces that dictate the selection and reinforcement of technology paradigms.

If an ecologically efficient solution is not available in both dominant and dormant paradigms¹⁴ then technology search may continue in new scientific domains that can lead to a radical innovation. This radical innovation if gets selected may lead to an eventual technology transition or paradigm shift for a particular problem set. The switching to a more efficient solution within and across technology paradigms is illustrated in Fig. 2

12 These are different from niches where radical innovations are developed keeping in view efficiency.

13 At the same time, a dominant solution may not be ecologically damaging in the short term if operated under the conditions of perfect and complete information and full optimization.

14 Mechanisms to altogether avoid such a situation by applying the precautionary principle are widely recognized. The precautionary principle is a widely accepted policy driver which led to the setting up of national and regional risk assessment and regulatory frameworks across countries. However the setting up of such national level regulatory framework is more often than not costly for low-income countries.

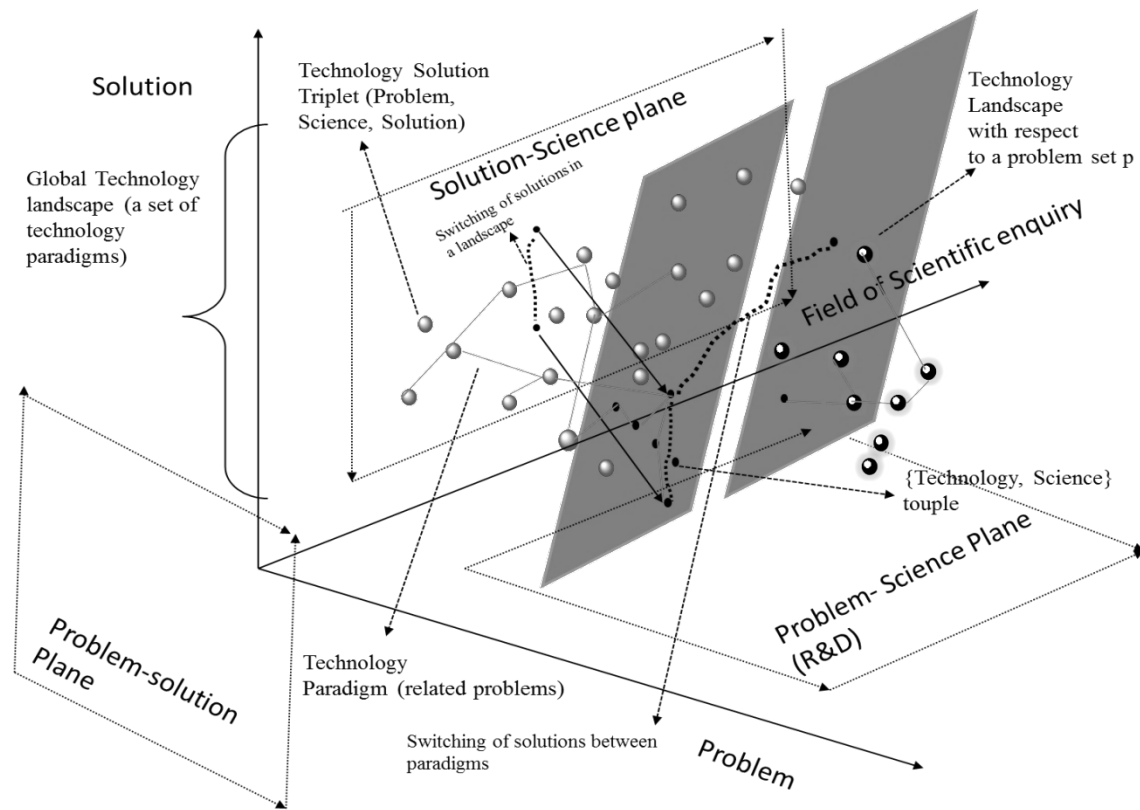


Figure 2 Switching between solutions

In this conceptualization a clear distinction is made between the innovation system (economic actors and ecology) where actors play out their economic efficiency strategies, Ecology plays its bio-physical efficiency strategy and the global technological landscape (domain of problems, science and solutions) wherein the technical change occurs as a result of those strategies.

Figure 3 depicts the process of technology evolution in a global technological landscape where technological search, emergence of problems, emergence and selection of a technology paradigms, and the ecological response. The emergence of a problem kick starts a technological search in the global technological landscape. A dominant paradigm emerges over time as a consequence of actions in the innovation system. Once the diffusion is complete because of the ecological response a dominant paradigm may engender new problems that undermine the production process. In order to solve the new problem switching is envisaged via search in the existing landscape (dictating the possible evolution of a trajectory), else in an existing paradigm (or a dominant paradigm), and in a dormant paradigm. If switching is not envisaged then altogether a new technological search in the global technological landscape gets initiated¹⁵ resulting in a major technology transition.

¹⁵ Niche innovations may get selected at this stage because of the window of opportunity (Geels and Kemp, 2007)

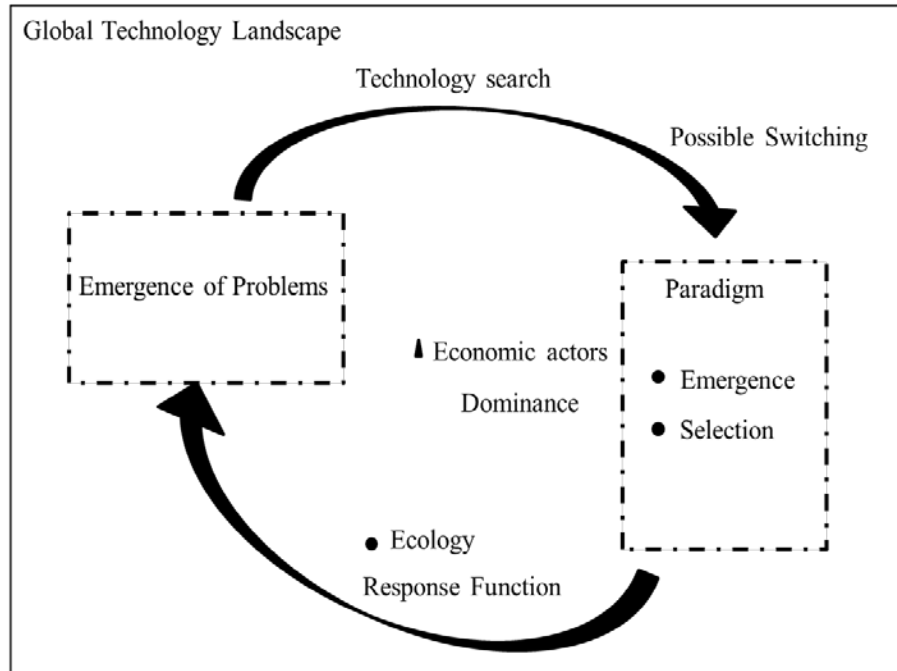


Figure 3 Technology paradigm shift

3. Application of the conceptual framework to agricultural production

Paradigmatic classification of industrial technologies is common in the innovation studies but is not so common in agriculture. This may be due to the proliferation of industrial (chemical and mechanical) as well as non-industrial (biological) technological solutions in the agricultural production. Some scholars do apply the evolutionary concepts of technology paradigms and trajectories to agriculture (Parayil, 1991, 1992, 2003; Possas, Salles-Filho, & da Silveira, 1996; Vanloqueren & Baret, 2009). However, an in-depth appraisal of transition dynamics using agricultural production is limited.

In this regard, Possas *et al* (1996) argue that applying the concepts of evolutionary economics, such as technological regimes and trajectories to agricultural innovation is very much relevant as it is characterized by heterogeneous sources of innovation (public and private actors) and the diffusion process by agent heterogeneity (farmers choosing a new technology or practice). Moreover, the rise of biotechnology coincided with a strong emergence of private sector reflecting the competitive asymmetries, like any other industrial sector and increased the degree of appropriability of innovations. While Parayil (2003) specifies green revolution and genetic engineering as different technological trajectories of a common technological paradigm, Vanloqueren and Baret (2009) consider agro-ecology¹⁶ and genetic engineering as different technological paradigms for analytical purposes.

In our own classification, we see agricultural production as being characterized by early green revolution technologies (MVs), late green revolution technologies (Hybrids),

¹⁶ OECD defines agroecology “as the study of the relation between agricultural crops and environment”.

biotechnologies (GM crops and biotech aided breeding techniques) and agro-ecological techniques (traditional, low input, organic farming practices). However, if the early and late green revolution paradigms are to be combined to represent a conventional paradigm of technologies before the advent of biotechnology we can clearly envisage the conceptual differences in the nature and makeup of the technological solutions being offered by each of these paradigms.

Problems: Any technological solution pertinent to agriculture can be labour saving or land saving. As emphasized in the earlier sections land saving technologies have been most appropriate in the developing country context as labour is abundant. Let us therefore examine the characteristics of the land productivity problem (yield) in depth. First and foremost the problem of yields is multifaceted. It is actually a set of interrelated and often overlapping problems such as inferior germplasm, susceptibility to insect pests and diseases (physiological), non-resilience to a given agro-ecology, and inability to produce more because of inferior morphological characteristics (for example weak stalks in field crops).

Areas of scientific enquiry: As the boundaries of basic sciences are continuously pushed by scientists the mode of solution delivery even to well-known problems keeps changing. The solution for better yields crops was derived from basic plant sciences with continuous selection and breeding of short dwarf varieties with best local cultivars based on the principles of Mendelian genetics¹⁷. But in practice technological solutions emerge as a result of developments in multiple scientific disciplines and more often than not there is an overlap of scientific principles involved in solution delivery.

During the early days of problem solving for improved yields, the area of focus of scientific enquiry remained fundamental plant sciences such as botany, plant biology, plant physiology (shape and size), plant pathology (susceptence to diseases), entomology (to analyse insect populations and their behaviour towards a host plant species). But as time passed advancements in plant genetics, molecular biology and bio-informatics lead to their application towards developing new crop varieties. Traits such as insect resistance and herbicide tolerance were achieved by insertion of alien genetic material. These plants were called genetically modified plants. Transgenic or GM crops¹⁸ were developed by the application of modern biotechnology methods to plant breeding. At the same time advancements in bioinformatics lead to the increased efficiency in research giving a facelift for the existing conventional R&D practices.

The solution design: The new plant types that are developed during the early green

17 As early as 1856, Gregor Mendel through his experiments with pea plants discovered that plant traits are passed from parents to off springs and therefore cross breeding between selected parents would produce off springs with desired traits.

18 International Seed Federation defines GM crops as “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”

revolution era had the capacity to respond to the application of fertilizers without lodging thereby enabling the plant to produce more grains per stalk. Subsequently the physiological and morphological characteristics of the plants were tweaked to make them suitable for agro-ecology. The morphological characteristics were redesigned painstakingly by crossing the existing cultivars with short dwarf and better yielding varieties in order to prevent the lodging thereby improving the possibility of higher yield per plant. Also making the crops respond to application of fertilizers was one of the key objectives, especially during the period of early green revolution. Crop responses to photo sensitivity, thermo sensitivity and a range of atmospheric parameters were analyzed to cater improvements in resilience. In particular, care was taken to develop varieties that showed better germination, uniform growth characteristics and faster production cycle. A combination of these methods of plant breeding became a dominant solution design. During the later years the rise of biotechnology provided advanced methods and tools to carry out plant breeding with precision and efficiency bringing about radical changes to the solution design.

Solution delivery/package: The solution for lower yields could appear in the form of solutions to each of the underlying sub-problems such as high yielding plant varieties, pesticides, fertilizers, herbicides or in the form of a genetically modified hybrid seed (that takes care of insects, weeds as well as higher yields). The solution package nevertheless comes with a package of practices that dictates its on-field implementation for optimal results.

Table 3 Classification of technology paradigms in agricultural production

	Conventional	Biotech	Agro-ecological
Solution package	Modern varieties, chemical fertilizers, pesticides + package of practices	GM seeds, chemical fertilizers + package of practices	Bio-fertilizers, bio-pesticides, integrated pest management, zero-tillage.
Solution model	Natural selection for desired traits	Marker assisted selection (DNA based) of genes for desired traits	Self-regenerative and eco-friendly models
Selected principles	Plant breeding	Transgenic or non-transgenic methods to achieve desired trait + Plant breeding	Minimizing the resource usage
Area of scientific enquiry	Plant Sciences (biology, plant physiology, botany, entomology) Chemistry	Modern biotechnology (micro-biology, bio-chemistry, genetic engineering) + traditional plant Sciences	Agro-ecological and environmental sciences

As Table 3 indicates though the problems overlap in all the three technology paradigms, other elements that constitute a technology paradigm, i.e, the areas of scientific enquiry, selected principle scientific field and their dominant solution design differ. There are differences in the solution delivery as well. Although the areas of scientific enquiry for green revolution (conventional) and genetic engineering (agri-biotechnology) paradigms overlap, molecular biology and genetical engineering indicate a radical departure from the earlier domains of traditional plant sciences. Agroecology on the other hand is based on the underlying principles of agronomy and ecology, the area of scientific enquiry lies in ecological sciences. The problem solving in agro-ecological domain often involve inputs and practices that maintain a balance between the farm and its ecology.

Under the conventional (green revolution) paradigm as discussed earlier solutions were searched in the areas of fundamental plant sciences such as botany, plant biology, plant physiology, plant pathology, entomology. These areas form the basis for any scientific endeavors in agricultural problems. Therefore some scholars view the modern agricultural biotechnology paradigm as an extension of conventional paradigm and that it is just a new trajectory with the same paradigm. But this viewpoint is narrow. Advancement in molecular biology, genetic engineering and interdisciplinary fields like bio-informatics made a huge difference to the process of problem solving. For instance, plant breeding in the conventional era involved the controlled modification of genetic makeup by natural means (natural pollen transfer between male and female lines) but in modern biotech methods, although the underlying sciences by and large remained the same, solutions like molecular markers and PCR (Polymer Chain Reaction)¹⁹ based on advancements in molecular biology are strikingly different. Advanced bioinformatics tools (genome databases) and techniques for mapping and precision analysis of DNA sequences have brought in major changes to solution design. Another significant divergence is the manipulation of genetic material by the introduction of genes from alien species into plants (via a gene gun or Agrobacterium mediated transformation) that is an outcome of advancements in genetic engineering.

Also a major difference came about in the mode of solution delivery with the collapse of trajectories involving synthetic inputs such as chemical fertilizers and pesticides. The rise of biological agents in lieu of synthetic or chemical agents changed the whole picture. The usage of Rhizobium, Pseudomonas, Trico derma Verde in nutrient fixation, and introduction of Bt protein by genetic modification in pest management are evidences for the same.

On the other hand, agro-ecological paradigm that includes organic farming and other eco-friendly practices is fundamentally different as the method of delivery of technological solutions is based on concepts of self-regenerative principles of ecological sciences. The steps involved in problem solving often involve technology and management practices that go beyond farm to its ecological environment. Hence it could be taken as a completely different technological paradigm. However Agro-ecological paradigm is punctuated by process innovations, that is, in farm management practices. Usage of crop residues, cattle manure as fertilizers, neem-seed oil and other biological extracts that serve as insecticides, protecting friendlier moths and other natural pest predators, using pheromone traps, light traps for insects are all part of the solutions

¹⁹ PCR is a laboratory technique used to make multiple copies of a segment of DNA. PCR is very precise and can be used to amplify, or copy, a specific DNA target from a mixture of DNA molecules (Nature.com website)

that belong to the agro-ecological paradigm.

Table 4 below gives an overview of the major forms of solution delivery under the classification.

Table 4 Major platforms of solution delivery in agriculture

Innovation	Green Revolution/Conventional	Biotech	Agro-ecological
Seed	Yes	Yes	No
Inputs	Yes	Yes	Yes
Process	Yes	No	Yes

Therefore, going by our construct of a technology paradigm, the areas of scientific enquiry, the dominant solution design, and the delivery platform all substantiate our classification.

So far the differences in the technology paradigms in agriculture and how agricultural innovations could be classified into three major paradigms are presented. Also explained is what constitutes a technology transition or a paradigm shift conceptually. We will now turn our attention to what a technology paradigm shift towards agricultural sustainability mean.

Sustainable agriculture is seen as an agricultural activity which is economically profitable for farmers, environmentally friendly and socially benefiting (Gómez-Limón & Sanchez-Fernandez, 2010; Hansen, 1996). Any agricultural technology or practice that contributes to the above mentioned characteristics of sustainable agriculture can be considered as a sustainable technology or practice. Hansen (1996) while presenting the story of sustainability in agriculture trace the origins of the philosophy to “the problems associated with conventional agriculture perceived as unsustainable gave rise to the notion of sustainability in agriculture”.

Environmental degradation and distributional asymmetries in the socio-economic impact are often the problems associated with the conventional technologies. At the same time, the potential of the modern biotechnology and agro-ecological practices, the two emerging alternatives towards improving the sustainability are being debated (Pinstrup-Andersen, 2001). The present day sustainability debates include the environmental degradation by conventional technologies, the long term economic, health and environmental impacts of genetically modified crops and the economic potential (lower than average yields) of the agro-ecological paradigm. Sustainability in agriculture therefore is determined by both economic as well as ecological outcomes of the production practices.

We will now attempt to substantiate our conceptualization of technology transitions by empirical analysis of the India’s experience with GR and GM transitions.

4. Empirical cases

4.1. Indian experience with green revolution or conventional paradigm

By the mid-1960s, due to population growth and lagging agricultural production there was severe shortage of food and a looming famine in India (Parayil, 1992). Consequently, to address this problem, there was a real search for the best agricultural technologies and practices to increase the production levels in cereals. Through cooperation between the Indian State, the CIMMYT (International centre for the improvement of Maize and Wheat, Mexico) and Indian agricultural scientists, the high yielding dwarf varieties of wheat (a radical innovation) developed at CIMMYT were adapted to the Indian agro-ecological conditions. These high yielding varieties along with the synthetic fertilizers formed a solution package called 'Green Revolution'. This solution package was intended to save the Indian agriculture from the trap of falling yields, hunger and poverty. With GR high yielding varieties (or modern varieties or MVs), yields could be substantially increased if used with controlled doses of chemical fertilizers and water. Therefore, initially, the MVs in rice and wheat were introduced in select regions best endowed with suitable agro-ecological conditions and irrigation infrastructure.

In the case of GR, the technological search in the global technological landscape happened in Mexico where renowned agricultural scientist Norman Borlaug discovered the 'short legs' varieties in Maize that can support greater amounts of grain on each stalk and those that mature early. This new variety was a radical technological breakthrough. These '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 mainly in the form of open pollinated varieties (OPVs) based on this dominant solution model. OPVs produce the off springs that have the same characteristics of the parents so that farmers can replant the seeds from harvest in the next season. OPVs dominated the Indian agriculture during GR.

Thereafter in the late GR period (from 1985) hybrid varieties were developed using a combination of the earlier GR methods, that is, using the same principle scientific fields of plant sciences, the dominant solution design was based on the principles of 'Mendelian genetics'²⁰ paving the way for a new technological trajectory within the GR paradigm. However the off springs of hybrid varieties do not have the same vigor as their parents and therefore the farmer should buy new seeds every season. The State and private firms paved the way for the development and diffusion of hybrid varieties in the late GR period

Parayil (1992) gives an extensive account of green revolution in India in which he highlights the importance of technological adaption of modern varieties and the role of public sector push in it. He also highlights the role of learning by social and institutional actors within the innovation system in the success GR. Reduction in market uncertainty by public procurement, supply of seed at lower prices, fertilizer subsidies and systemic features like increase in research investments, expansion of public sector R&D in developing HYVs, increase in the domestic demand fuelled the diffusion of GR technologies. In other words the alignment

of actor strategies, policies, institutions and markets in the innovation system promoted GR in a big way during the 1970s and 1980s. In addition to these factors lack of efficient competing technology reinforced the strength of the paradigm. That is, while the economic actors in the innovation system through their strategic actions ensured the selection of GR as a preferred technology paradigm while the systemic forces allowed it to become a dominant one.

The success of GR in developing countries including India is well documented (Evenson & Gollin, 2003; Pinstup-Andersen & Hazell, 1985). Evenson and Gollin (2003) in their study of the impact of GR during the years 1960-2000 show strong evidence of the productivity increase (though uneven across crops and regions) and lowering food prices across developing countries.

Since the literature on GR in India is vast specific literature corpus is identified using four sources: Econlit, Econpapers, Scopus (Economics) and Planning Commission Reports (Government of India). The search criteria applied was 'journal articles' and reports with the words 'Green revolution' and 'India' appearing in 'title', 'keywords' or 'abstract' which is a standard practice for bibliometric analysis. The corpus is further filtered to retain only the most relevant articles that explicitly discussed the long term socio-economic and ecological impacts of GR in India in the context of sustainability (the corpus is presented in Appendix Table A1)

The sustainability aspect of technology paradigms has both economic and ecological dimensions. Studies focusing on the economic efficiency of technological systems usually study the outcomes in terms of yields, profits. Besides the studies focusing on yields, income and poverty reduction most of the articles evaluating the economic impact of GR in India estimate the TFP growth. An increasing TFP over time implies that output is growing at least as fast as the inputs (Lynam & Herdt, 1989). A stagnant or decreasing TFP indicates that output increases are being primarily driven by increased use of inputs rather than by technological improvements. This, in turn, means that in order to sustain production levels at a given level if TFP decelerates then more inputs are needed to maintain the output levels leading to resource degradation. Evidently, under this scenario the production system is not sustainable (ecologically or economically) in the long run. In other words, the principal assumption in applying TFP estimates is that a positive trend in TFP growth over a period of time indicates a sustainable production system. That is, if TFP growth is found to be stagnant or decelerating the following scenarios are possible i) Higher yields indicate that the output is being primarily driven by the growth in inputs rather than technological improvements ii) Decreasing yields per hectare indicate that more and more inputs are needed to maintain higher levels of output leading to resource degradation. The findings of the meta-analysis of the impact literature are summarized in Table 5.

Table 5 Impact of Green Revolution in India

Description	Count	% of Total
Total number of articles considered for analysis (corpus)	20	100
Only dealing with economic performance	13	65

Only dealing with ecological outcomes	4*	20
Discussing both	6*	30
Impact on yield and TFP		
Yield increase	20	100
Uncertain about increase in yield or indicating decrease in yield	0	NA
Increasing TFP growth (i.e. acceleration of productivity)	3	15
Decreasing/stagnant TFP growth (in late GR period or during the 1980's)	6	30
Generation of ecological externalities		
Asserting improved ecological conditions	0	NA
Doubtful or concerned about negative impact on ecology	7*	35

Note: While some of the articles discuss the direct evidence of environmental degradation, few propose the stagnant/negative growth in TFP as being indicative of resource degradation.

As can be seen from the Table 5, even though there is a strong consensus on the yield increase, some of the studies estimate a negative or stagnant TFP growth especially in the high yielding regions of India (see Table 6 for details). At the same time not all TFP studies indicate negative growth, as the results depend on the chosen methodology, output and regions (Coelli & Rao, 2005).

At the same time, the TFP estimations do not explicitly incorporate ecological externalities. Byerlee and Murgai (2001) present the limitations of using TFP measures for sustainability evaluation of agricultural systems. They argue that only studies combining both long term productivity measurements as well as resource quality indicators can effectively measure the sustainability of agricultural technology systems. Table 6 summarizes the findings of studies investigating the sustainability of aggregate and individual cropping systems in India. The results indicate a decelerating TFP growth in certain high yielding regions highlighting the sustainability issues of the GR paradigm.

Table 6 Literature on Total Factor Productivity estimation during GR in India

Author/ Year	Output	Type of study	Regions	Methodology	Years	Major Conclusion	Regions pertinent to the conclusion
Rosegrant and Evenson (1995)	5 major food crops	Country specific	All India	Tornquist-Theil Index	1956-1987	Positive trend in TFP growth	All India
Janaiah <i>et al</i> (2005)	Rice	Country Specific	9 major states	Tornquist-Theil Index	1970-1985	Negative TFP growth	Bihar
					1985-2003	Negative TFP growth	Punjab, Karnataka, Madhya Pradesh
Kumar and Jha (2005)	Rice	Country specific	11 major states	Tornquist-Theil Index	1971-1991	Deteriorated TFP growth between 1971-80 and 1980-91	Bihar, Haryana, Punjab
Kumar and Mittal (2006)	8 crops* *Results for rice alone are presented	Country Specific	16 major states	Tornquist-Theil Index	1971-1986	Stagnant /Decelerating TFP growth	Bihar, Karnataka, Madhya Pradesh, West Bengal
					1986-2000	Stagnant/Decelerating TFP growth	Assam, Karnataka, Uttar Pradesh, Punjab, Haryana
Mukherjee and Kuroda, (2003)	30 crops	Country Specific	14 major states	Tornquist-Theil Index	1973-1993	Stagnant /Decelerating TFP growth	Bihar, Uttar Pradesh, Punjab, Rajasthan
Murgai <i>et al</i> (2001)	Rice and Wheat	Inter country – Region specific	Punjab regions of India and Pakistan	Tornquist-Theil Index	1966-1994	Rapid yield growth primarily due to growth in inputs	Indian Punjab
Bhalla and Singh (2010)	44 crops	Country specific	17 major states – a district level study	NA	1980-83 to 1990-93	NA	
					1990-93 to 2000-03	Deceleration in yield and total output	All states except Gujarat and Maharashtra
Aggarwal <i>et al</i> (2004)	Rice and Wheat	Region specific	Indo -Gangetic plains (IGP)	NA	1980-1999	Positive trend in TFP growth	Indo Gangetic Plains

Moreover, production statistics show that production in rice and wheat, the basic cereal crops in India, is flattening (see Figure 4). The flattening of production (plateauing effect) of these major cereals is attributed to the falling productivity, the fatigue in high yielding variety development and degradation of soil and ground water resources in the high yielding regions of Haryana and Punjab (Dhillon, Kataria, & Dhillon, 2010; Murgai et al., 2001; Nagarajan, 2005).

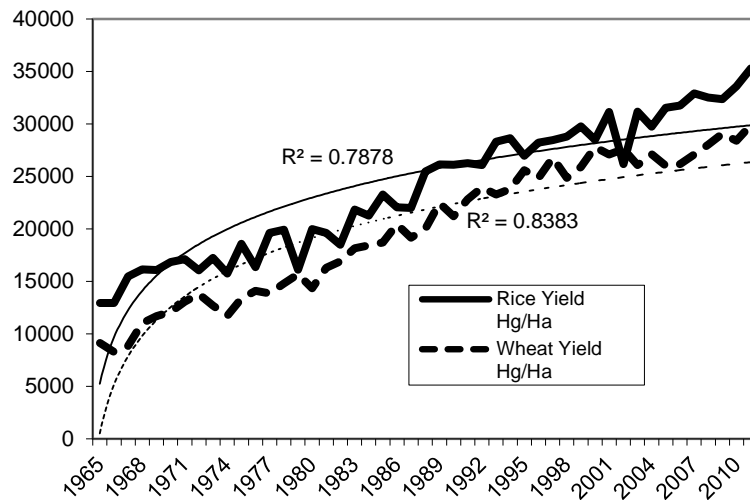


Figure 4 Plateauing of Rice and Wheat yield in India (hectograms per hectare) with a logarithmic trend line (*FAOStat*)

Therefore despite its initial success, during the past two decades GR increasingly came under scrutiny for two reasons. First, the average yield per hectare of essential food crops has reached a plateau and total factor productivity growth is decelerating in the late GR period (starting mid 1980s) in the high yielding regions (Janaiah et al., 2005). Second, GR increased the stress on natural resources, lowering soil fertility and ground water levels especially in the high-yielding regions (Dhillon et al., 2010). Both these effects raised serious sustainability concerns of GR technologies. This in turn shifted both research and policy focuses to look beyond food availability to explore how sustainability of agricultural production may be guaranteed via newer technologies.

The analysis of the GR literature so far tossed out two important empirical points, first, the average yield per hectare of essential food crops has reached a plateau and TFP growth is decelerating in the high yielding regions (see Table 6). Further, claims that GR increased the stress on natural resources and has tremendously lowered soil fertility and ground water levels, especially in the high-yielding regions also became evident (Dhillon et al., 2010). Let us now look at the latter claims.

Excess usage of chemical fertilizers increases the hard residues in the soil thereby severely affecting the intake of soil nutrients in required proportions by the plant. India stands tall globally in the consumption of chemical fertilizers following China and the US with a

consumption of 17.9 metric tonnes between 2002 and 2005. Between 2006 and 2007 this figure reached 23.6 metric tonnes. Between 2002 and 2008 the reported annual growth in the usage of Nitrogen, Phosphates and Potash as independent fertilizer nutrients in India are 6.4, 7.3 and 12.6 respectively (*FAOStat*). These levels are significantly higher in the irrigated regions as compared to rainfed regions raising concerns of soil degradation in these regions.

Singh (2000) finds that in Haryana the expansion of agricultural productivity during GR came at the cost of severe soil and water degradation. The higher use of inputs partly stems out of lack of awareness about their negative long term effects of the overuse on soil properties. Besides this imperfect information, discounting of the future economic returns for higher returns in current time period also seems to be a problem. Less informed farmers simply think application of higher levels of inputs gives more returns. Therefore the sustainability problem is partly the technology itself and partly the implementation. In this regard, Dyson (1999) claims that the higher dependence on chemical fertilizers and consequent soil fertility loss is can cause severe cereal shortfalls in South Asia. His estimates show that by the year 2025, South Asia (of which India constitutes 70% of population) falls short of 25 million tons of cereals given the population, income growth and current technological paradigm that increase the dependence on chemical fertilizers, especially Nitrogen.

Ground water resources play a crucial role in the agricultural production and excessive usage of ground water resources causes long term sustainability concerns. GR practices also led to higher consumption of fresh water resources especially in the high yielding regions of Punjab and Haryana (Agoramoorthy, 2008). Inefficient water management can lead to water logging which results in the farm soil being salinized. In India the soil salinized by irrigation stood around 3 million hectares while the total area waterlogged by irrigation stood at 2 million hectares (*FAOStat*).

GR also led to intensification and mono-culture practices where farmers stick to the same high yielding variety every cropping season. Mono-culture of crop varieties can limit the availability of diverse genetic base and can also cause loss of varietal virility due to natural ecological evolution. The pests and pathogens get used to the variety and evolve themselves to make the particular variety susceptible.

Aggarwal et al (2004) in their study on adaptation strategies of Indo-Gangetic plains to the emerging environmental changes indicate that the deceleration in TFP was majorly due to higher usage of inputs. Further citing Pingali and Shah (1999), Aggarwal et al. (2000) and Hobbs and Moris (1996) they state that the mono-cropping of the cereal varieties has tremendously increased the pest, disease and weed incidence in the rice-wheat system of India.²¹ This clearly shows that the GR diffusion witnessed the negative ecological 'response' in the form of evolution of pests, pathogens and weeds for popular GR varieties that undermine future production.

In sum, our assertion that a dominant technology underlying a production process can

2121 The pests include aphids, stem borers, diseases include Heliothis, false smut, sheath rot, sheath blight, spot blotch, foliar blights, head scab, and Karnal bunt and *Phalaris minor* has become a major weed resistant to most herbicides (Aggarwal et al., 2004)

trigger ecological externalities generating new problems that undermine the production process is more than realized in the case of GR transition in India. In addition, the analysis of GR transition also demonstrates that the actions of the economic actors in the innovation system contributed not only for the selection and stability of the paradigm but also the fall out (via inefficient implementation of technologies).

4.2. Indian experience with Bt cotton (agri-biotech paradigm)

By the start of the new millennium cotton yields in India were among the lowest in world. The consumption of pesticides by cotton cultivation was as high as 54% of the total pesticide consumption in the country driving the cost of cultivation higher up (Raghuram, 2002).

In this new problem context the initial technology search in the global technology landscape happened in 1911, in Thuringia, Germany. There, scientists discovered that *Bacillus thuringiensis* (Bt), a bacterium acts as a natural insecticide against a local pest ‘flour moth’. This led to development of a sprayable Bt pesticide first in France and later in US in 1938 and 1950 respectively. This was the starting point of a major change in the solution design for pests (application of Bt instead of synthetic pesticides)

A major breakthrough happened in 1982, when scientists at Monsanto isolated the *cry* family genes from Bt that are responsible for the production of the toxin. Simultaneously elsewhere in the global technological landscape advanced scientific methods of analysing and working at the level of DNA came about in the form of marker assisted selection, PCR etc, and methods of transferring genes from other species into plants via *agrobacterium tumefaciens* mediated transfer. A combination of these factors led to a major technological breakthrough in plant protection technologies when scientists at Monsanto successfully incorporated the genes from Bt into plants via transgenesis. By 1996, Monsanto commercialized Bt varieties in cotton in the US with great success.

In March 1995, Indian government gave the initial authorization for developing a Bt version of cotton in India. In 1998, Monsanto obtained a 26% stake in Mahyco, an Indian firm for the purpose of introducing its Bt technology into Indian market. In 1998, the Department of Biotechnology approved the small scale field trials of Bt cotton and later in July 2000, it granted permission to conduct large-scale field trials. Two years later, in March 2002, the Genetic Engineering Approval committee (GEAC) approved the commercialization of three varieties of insect-resistant Bt cotton hybrids (Mech-12, Mech-162 and Mech-184) developed by Mahyco in collaboration with Monsanto.

Since the introduction of Bt cotton in India despite the raging discussions on the socio-economic impact its diffusion was spectacular showcasing the making of a radical technology into a market dominating one. The planted area with Bt cotton increased from less than 10 percent of the total cotton area in 2004 to more than 95 percent in 2013 (Choudhary & Gaur, 2010; James, 2013). This enthusiasm of farmers signalled not only the market success for this technology but a major technological transition as local firms invested in developing a range of Bt crops in vegetables as well as field crops by either licensing or developing their own Bt technology. This favourable alignment of innovation system actors (except some NGOs),

policies and institutions (regulatory) made the diffusion of Bt cotton a major success in India.

Coming to the outcomes of Bt cotton diffusion a meta-analysis of literature was carried out on the impact of Bt cotton in India using Econlit, Econpapers, Scopus (Economics) and NGO reports with the search criteria being 'Bt or Bacillus Thuringensis' or 'GM or Genetically modified' and 'cotton' and 'India' appearing in the title, keywords or abstract. Again, a second round of filtering was done to retain studies that explicitly discussed the long term socio-economic and ecological impacts of Bt cotton in the India (see Appendix Table A2 for the final corpus). A majority of these studies are cross sectional in nature based on farm level data gathered during single or multiple cropping seasons in diverse agro-ecologies of India. Table 7 summarizes the findings from the literature.

Table 7 Impact of Bt cotton in India

Description of the corpus	Count	% of Total
Total number of articles considered for analysis (corpus)	35	100
Only on economic performance	33	94.3
Only on ecological outcome	1*	2.8
On both	4*	11.4
Impact on Yield		
Yield increase	31	88.6
Uncertain about increase in yield or indicating decrease in yield	3	8.6
Generation of ecological externalities		
Asserting improved ecological conditions	3*	8.6
Doubtful or concerned about negative impact on ecology	2*	5.7

Note: A Majority of studies discuss positive ecological impact in terms of improved health due to reduced pesticide usage (positive effect), and negative in terms of increase in pest incidence in Bt cotton

The literature on Bt cotton in India to a large extent shows that the pesticide requirement for bollworms reduced, yield is enhanced and profits have increased for the adopters. However there is overwhelming evidence that the cost of cultivation with Bt cotton hybrids has gone up significantly. Yet the higher profits for the adopters are found to be driven by the increase in the yields which compensated for the raise in costs. The pesticide reduction effect for bollworms is shown to be positive over the years in several studies (Barwale, Gadwal, & Zehr, 2004; M. Bennett, Kambhampati, Morse, & Ismael, 2004; R. Bennett, Ismael, & Morse, 2005; Richard Bennett, Kambhampati, Morse, & Ismael, 2006; Gandhi & Namboodiri, 2009; Kathage & Qaim, 2012; Krishna & Qaim, 2012; Loganathan, Balasubramanian, Mani, & Gurunathan, 2009;

Narayanamoorthy & Kalamkar, 2006; Sadashivappa & Qaim, 2009; Subramanian & Qaim, 2009).

While the development of severe resistance in the bollworms for the Bt toxin is not a reported problem in India (Kranthi, 2012), the resistance in Pink bollworms (*Helicoverpa Armigera*) became evident in 2009 (Monsanto, 2009). Though the introduction of Bt hybrids with stacked genes of Cry1 Ac and Cry2 Ab (which is an innovation in the same trajectory) by Monsanto in 2006 can arguably defer the development of resistance in other target pests it is yet to be seen. However, concerns regarding the susceptibility of Bt cotton hybrids towards sucking pests²² became apparent through the farm level studies. Also empirical evidence that pesticide sprayings for secondary pests were either maintained at the same level or increased became apparent (M. Bennett et al., 2004; Kiresur & Ichangi, 2011; Krishna & Qaim, 2012). Also a hitherto unseen pest in India, a mealybug (*Phenacoccus solenopsis*) started infesting Bt cotton in 2006 causing considerable damage to the crops (Nagrare et al., 2009).

Although the GM paradigm is yet to become a dominant one in Indian agriculture, the analysis substantiates the idea that the response function of ecology can cause new set of problems that necessitates a technology switch or a new technological search.

5. Conclusion

The area of evolutionary economics has borrowed its core set of its ideas from classical theory of evolutionary biology. While the normative concepts of variance, natural selection (self-organization), and survival of the fittest are the majorly ‘applied’ concepts to explain the rise and fall of economic actors, it is necessary to integrate the concepts of natural (biological or bio-physical) evolution literally into discussions of technological evolution (Phillips and Su, 2007). This is important to understand and explain the technology transitions in agricultural production. This idea is also important to drive the system towards sustainable transition, particularly the bio-economy where natural pests, viruses and physical elements such as soil, water and air are part of the production processes.

Standard representations of innovation system include usual economic actors. In addition, ‘Nature’ must also be considered as an actor in the 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 as an actor via productivity. Second, the state of nature is impacted by the actions of economic actors in the innovation system. At the same time, as an actor in the innovation system, Ecology is distinct from other economic actors. While the play of economic actors may be predictable 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 based on the existing science base. Therefore it is necessary to view the evolutionary responses of nature (that strive to achieve biophysical efficiency) along with the evolutionary behavior of economic actors trying to achieve economic efficiency. Thus as ecological economists have long argued the integration of ‘Ecology’ in the economic system or in our case the ‘innovation system’ is necessary to study

22 Aphids, jassids and white fly are the non-bollworm pests that attack cotton popularly known as ‘sucking pests’ as they suck the sap out of stems and leaves.

sustainable technology transitions.

Lastly, the empirical analysis substantiated the following. First, a production problem can kick-start a technological search in the global technological landscape giving rise to radical technological breakthroughs (semi-dwarf varieties during green revolution and isolation of cry1AC from *Bacillus thuringiensis*). As selection occurs via the innovation system actors, the technologies diffuse. Historical events and systemic forces such as (great public sector push in the case of GR, private sector catch-up and farmer enthusiasm in the case of Bt cotton) ensure the stability of the paradigms. However the ecological response to sub-optimal technologies or their implementation gives rise to a new set of problems that undermines the future production. At the same time, evolution of the scientific domains allows for the technological search to continue outside a dominant paradigm (outside the traditional plant sciences in case of GR) which make the conditions in the global technological landscape seemingly appropriate for the emergence of a new paradigm (the genetically modified crops).

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Appendix

Table A1 Literature corpus on impact of Green Revolution in India used for meta-analysis

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Table A2 Literature corpus on impact of Bt cotton in India used for meta-analysis

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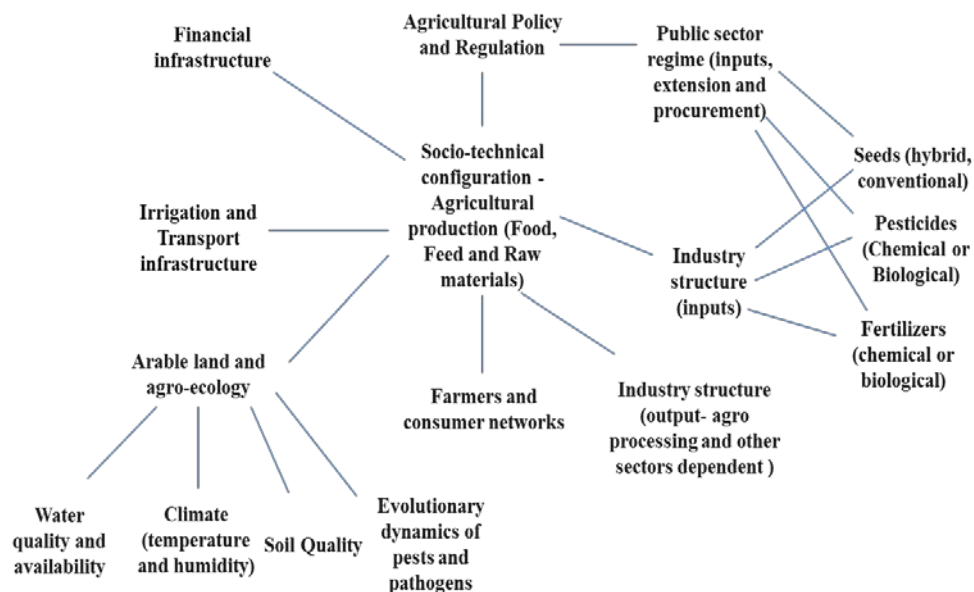


Fig. A1 Socio-technical configuration of agricultural production in the tradition of socio-technical systems (Geels, 2002)