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How agricultural research systems shape a technological regime that develops genetic engineering but locks out agroecological innovations

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ABSTRACT

Agricultural science and technology (S&T) is under great scrutiny. Reorientation towards more holistic approaches, including agroecology, has recently been backed by a global international assessment of agriculture S&T for development (IAASTD). Understanding the past and current trends of agricultural S&T is crucial if such recommendations are to be implemented. This paper shows how the concepts of technological paradigms and trajectories can help analyse the agricultural S&T landscape and dynamics. Genetic engineering and agroecology can be usefully analysed as two different technological paradigms, even though they have not been equally successful in influencing agricultural research. We used a Systems of Innovation (SI) approach to identify the determinants of innovation (the factors that influence research choices) within agricultural research systems. The influence of each determinant is systematically described (e.g. funding priorities, scientists' cognitive and cultural routines etc.). As a result of their interactions, these determinants construct a technological regime and a lock-in situation that hinders the development of agroecological engineering. Issues linked to breaking out of this lock-in situation are finally discussed.

1. Introduction

Science and technology are at the core of agricultural change. Fundamental and applied research in biology, chemistry and genetics has resulted in a constant flow of innovations and technical changes that have greatly influenced agricultural systems.

However, the direction of agricultural science and technology (S&T) is now under great scrutiny. International scientific assessments have demonstrated the increasing global footprint of agriculture, including its contribution to climate change (IPCC, 2007; Millennium Ecosystem Assessment, 2005), while non-governmental organizations and scientists have long called for radical changes in this field (Union of Concerned Scientists, 1996; Food Ethic Council, 2004; European Science Social Forum Network, 2005). Yet now, a radical change has been recommended. The International Assessment of Agricultural Science and Technology for Development has recently and officially called for a reorientation of agricultural science and technology towards more holistic approaches, after a 4-year process that involved over 400 international experts (IAASTD, 2008). This panel has already been compared to the Intergovernmental Panel on Climate Change, both for the quality of its governance and the importance of its recommendations, which are straightforward: "Successfully meeting development and sustainability goals and responding to new priorities and changing circumstances would require a fundamental shift in agricultural knowledge, science and technology". Furthermore, the IAASTD calls for greater support of agroecological approaches, which it considers a great potential for world agriculture. In contrast, the role of genetic engineering was the sole element of controversy in the final statement, which is weak on this point.

If the IAASTD recommendations, as well as those of the IPCC and Millennium Ecosystem Assessment, are to be taken seriously and implemented, we need to understand why the current agricultural S&T landscape has not sufficiently supported holistic and agroecological approaches, while other agricultural innovations, such as transgenic crops, were able to flourish.

In this paper, we focus on the development of genetic engineering and agroecology, two important trends within biological and agricultural sciences during the second half of the twentieth century. Both genetic engineering and agroecology were insignificant or non-existent scientific branches before the early 1970s. Scientists and public authorities could theoretically see them as two complementary fields of research with equal potential to improve agricultural systems. Genetic engineering and its vital complementary discipline molecular biology have

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attracted more research funds than agroecology in recent decades. Agroecology has not acquired such momentum although its influence is also growing (Parrott and Marsden, 2002; Pretty et al., 2003).

It is beyond the scope of this paper to assess the advantages and drawbacks of the two trends. What drove us to compare them is the necessity to explain their development differential. Is this differential only due to the intrinsic superiority of genetic engineering compared with agroecology, or can it be methodologically explained by other factors? If so, which ones?

The use of concepts from the evolutionary line of thought (evolutionary economics) – such as technological paradigms and trajectories, technological regimes, path dependence and lock-in – is vital in explaining this development differential.

In Section 1, we discuss genetic engineering and agroecology as two technological paradigms that make sense and science. Technological paradigms are a concept taken from the study of industrial innovations that has seldom been used to analyse agricultural innovations. In Section 2, we explain how a Systems of Innovation (SI) approach can be used to analyse the factors (determinants of innovation) that influence the choice of technological paradigms as well as the development of technological trajectories within agricultural research systems (ARS). Section 3 is the systematic description of these determinants, whose combination induces an imbalance between genetic and agroecological engineering. ARS emergent properties such as path dependence and lock-in are analysed in Section 4. Finally, we discuss the issues arising from our observations.

2. Technological paradigms and trajectories, from factories to farmers' crops

2.1. Technological paradigms and trajectories

The concepts of 'technological paradigms' and 'technological trajectories' have been suggested by Dosi (1982) to allow research to go beyond the 'demand-pull' and 'technology-push' theories of technological change. While Dosi initially introduced his concepts in the field of technological change within industrial structures, it has later been argued that they could be extended to agriculture (Possas et al., 1996).

Dosi defined a technological paradigm as a "model and a pattern of solution of *selected* technological problems, based on *selected* principles derived from natural sciences and on *selected* material technologies". A technological paradigm defines an idea of 'progress' by embodying prescriptions on the directions of technological change to pursue and those to neglect. This is a broad analogy with the Kuhnian definition of a scientific paradigm which determines the field of enquiry, the problems, the procedures and the tasks (Kuhn, 1962). A technological trajectory is the "pattern of normal problem solving activity (i.e. of progress) on the ground of a technological paradigm" or, in other words, the improvement pattern of concrete solutions based on a paradigm.

Applications of these concepts in agriculture vary widely. Parayil (2003) described the Green Revolution and the Gene Revolution as two technological trajectories.[1] Biotechnology, including agricultural biotechnologies, was soon presented as a new technological paradigm (Russel, 1999) and several authors have analysed particular technological trajectories in agrochemical and agro-biotech industries (Joly and Lemari, 2004; Chataway et al., 2004).

[1] Some authors refer mainly to the concept of technological trajectories while others use technological paradigms, but the logic is the same as trajectories signify progress along a paradigm.

2.2. Genetic engineering and agroecology, or 'agroecological engineering'

So far, genetic engineering and agroecology had not been compared as two technological paradigms that rely on two different scientific paradigms, pursue different objectives and are composed of different subtrajectories (Table 1).

Genetic engineering is the deliberate modification of the characteristics of an organism by the manipulation of its genetic material. The main technology upon which this process is based is transgenesis, following the discovery of the recombinant DNA technique in 1973. The best known applications of genetic engineering in agriculture are transgenic herbicide-tolerant plants, soybean or insect-resistant *Bt* maize in the USA. The fundamental strategy in genetic engineering is to modify the plants to allow them to be productive in adverse conditions caused, for instance, by pests, pathogens, drought, saline environments and unfertile soils; or to design plants for new objectives such as plants with altered nutritional contents. This goal fits the scientific paradigm that underlies genetic engineering that is reductionism. Genetic engineering has been described as a new technological paradigm (Orsenigo, 1989), although this conceptualization has not yet been much explored in the literature.

Transgenic crops are now grown on 114 million hectares in 23 countries, 11 years after their introduction (James, 2007). The progress of genetic engineering has been relatively fast. In the US, the number of field trial permits issued rose from 0 in 1986 to 107 in 1991, to more than 1000 every year since 1998, totalling already 12 000 field trials permits in 2005 (Information Systems for Biotechnology, 2006).

Agroecology emerged from the convergence of ecology and agronomy (Dalgaard et al., 2003). It is the application of the ecological science to the study, design and management of sustainable agroecosystems (Altieri, 1995). We use the term 'agroecological engineering' in this paper to put the two technological paradigms on an equal footing. 'Agroecological engineering' refers to the fact that agricultural systems can be 'engineered' by applying agroecological principles, just as plants are 'engineered' by transgenesis in 'genetic engineering'. The term 'Agroecological engineering' has seldom been used, except occasionally in China (Yan and Zhang, 1993).

Agroecological engineering is an umbrella concept for different agricultural practices and innovations such as biological control, cultivar mixtures, agroforestry systems, habitat management techniques (for instance, strip management or beetle banks around wheat fields), or natural systems agriculture aiming at perennial food-grain-producing systems. Crop rotations, soil fertility improvement practices, mixed crop and livestock management and intercropping are also included. Some applications involve cutting-edge technologies while others are old practices (for instance, traditional systems that provide significant insights to agroecology). Globally, hundreds of agricultural systems are based on agroecological principles—from rice paddies in China to mechanized wheat systems in the USA, although data are not as accurate as for transgenic crops acreage (Parrott and Marsden, 2002; Pretty et al., 2003).

The scientific paradigm on which agroecological engineering relies is ecology (and holism). The objective is to design productive agricultural systems that require as few agrochemicals and energy inputs as possible, and instead rely on ecological interactions and synergisms between biological components to produce the mechanisms that will enable the systems to boost their own soil fertility, productivity and crop protection (Altieri, 1995). Some aspects of agroecological engineering may be related to biomimicry (Benyus, 1997). While the objective of genetic engineering is to improve only a single element of the agroecosystem (modifying

Table 1
Genetic engineering and agroecological engineering are two different technological paradigms.

Technological paradigms	Genetic engineering	Agroecological engineering
Basic definition	Deliberate modification of the characteristics of an organism by the manipulation of its genetic material	Application of ecological science to the study, design and management of sustainable agroecosystems
Implicit objective	Engineering plants: modify plants to our best advantage by making them productive in adverse conditions or by designing them to fit new objectives	Engineering systems: improve the structure of an agricultural system to make every part work well; rely on ecological interactions and synergisms for soil fertility, productivity and crop protection
Scientific paradigm underlying the technological paradigm	Reductionism	Ecology and holism
Examples of subtrajectories progressing along the technological paradigm	Bt insect resistant plants, herbicide-tolerant plants, virus-resistant plants etc.	Biological control, cultivar mixtures, agroforestry, habitat management techniques etc.

existing plants or designing new plants), the objective of agroecological engineering is to improve the structure of the agricultural system and "*to make every part of the structure work well*" (Liang, 1998).

In a dynamic perspective, three conceptual levels may be discerned: (1) the two technological paradigms, genetic engineering and agroecological engineering, (2) the technological trajectories (the progress within these two paradigms), and (3) the various subtrajectories (the concrete implementations of each paradigm, meaning Bt-resistant and herbicide-resistant plants for genetic engineering, agroforestry and habitat management strategies for agroecological engineering.

2.3. *Paradigms and the real world*

The comparison of two broad and archetypal paradigms may seem too caricatural or simplistic to be useful. Yet the dual opposition between genetic engineering and agroecology already exists in the real world, both in science and in society. Proponents of both paradigms claim that their paradigm is the only one able to feed the world and solve environmental issues, and that the other paradigm puts the world at great risk. Paradigms consequently influence science and technology choices. This fact justifies using these concepts in a comparative framework.

Several authors have used paradigms to analyse the models at stake in the agrifood sector. Lang and Heasman (2004) have convincingly put forward the concept of 'food paradigms'. They have argued that the 'Life Sciences Integrated paradigm' and the 'Ecologically Integrated paradigm' were competing to replace the 'Productionist paradigm' in food systems. Allaire and Wolf (2004), who focus on food innovations, similarly picture three 'innovation paradigms': an old one (the mass-production and consumption Fordist model) and two new ones (the first is represented by the segmentation of products within supermarkets, and the second by products with strong identities such as those available on farmer markets). The competition between rival 'agrifood paradigms' has also been put forward by Marsden and Sonnino (2005) and Morgan et al. (2006). This point of view has already been used to analyse the debate about the possibility of coexistence between genetic engineering and alternative agricultures (Levidow and Boschert, 2008). Such analyses avoid a fake black and white vision of the agrifood sector. In reality, they enable researchers to analyse the trends and choices at stake in the agrifood sector, all of which is vital for democratic S&T choices.

Our analysis focuses on agricultural innovations. This scope is therefore much more limited than the agrifood paradigm perspectives chosen by the authors mentioned above.

Three remarks must be made as the real world is obviously not as clear-cut as theoretical concepts:

- Hybrid situations exist. Systems biology, for instance, focuses on interactions between components of biological systems, such as the enzymes and metabolites in a metabolic pathway. It thus combines a focus on ever-smaller levels of the living systems (from molecular biology and reductionism) with an interest in interactions (from the systems approach).
- Within trajectories, there is a wide spectrum of diversity. For instance, biological control of insects can result in innovations such as the mass release of predator insects, which are an efficient intervention but have no impact on the practice of monoculture, an important cause of insect problems. If designed in the agroecological paradigm, biological control can lead to habitat management solutions (landscape ecology) such as beetle banks and strip management, which have a structural effect on disease control (i.e. Levie et al., 2005). Some agroecological approaches may also be used in conventional systems. In practice, agricultural innovations are used in agricultural systems with various degrees of closeness to agroecological principles. In fact, farmers combine various types of innovations that stem from different trajectories.
- Agroecological engineering is not to be confused with organic farming. Organic farming has many principles in common with agroecology. Organic farmers have implemented many agroecological innovations in their crops, although they may in certain cases also replicate the productivist approach that goes against agroecological principles (Guthman, 2000; Dupuis, 2000).

3. How agricultural research systems shape innovation choices

One of the main questions behind Dosi's concepts of technological paradigms was "How does a paradigm emerge in the first place and how was it 'preferred' to other possible ones?" (Dosi, 1982). Dosi's hypothesis was that the economic forces together with institutional and social factors operate as a 'selective device' (selection environment) by influencing criteria such as feasibility and profitability at each level, from research to development.

Dosi's selective device has been overshadowed by a similar yet stronger concept of technological regime. Technological regimes are the (sets of) rules of the game that guide the direction of technological innovation and use (Possas et al., 1996).[2]

Different approaches have analysed the various factors shaping the technological regime: the relative price of resources (Hayami

[2] According to Possas et al., the current technological regime of modern agriculture is the evolutionary result of the intersection of different trajectories that have reached a growing technological coherence over the last 150 years. These developments involve industries (pesticides, fertilizers, seeds, and machinery), public research and educational institutions producers and producer organizations.

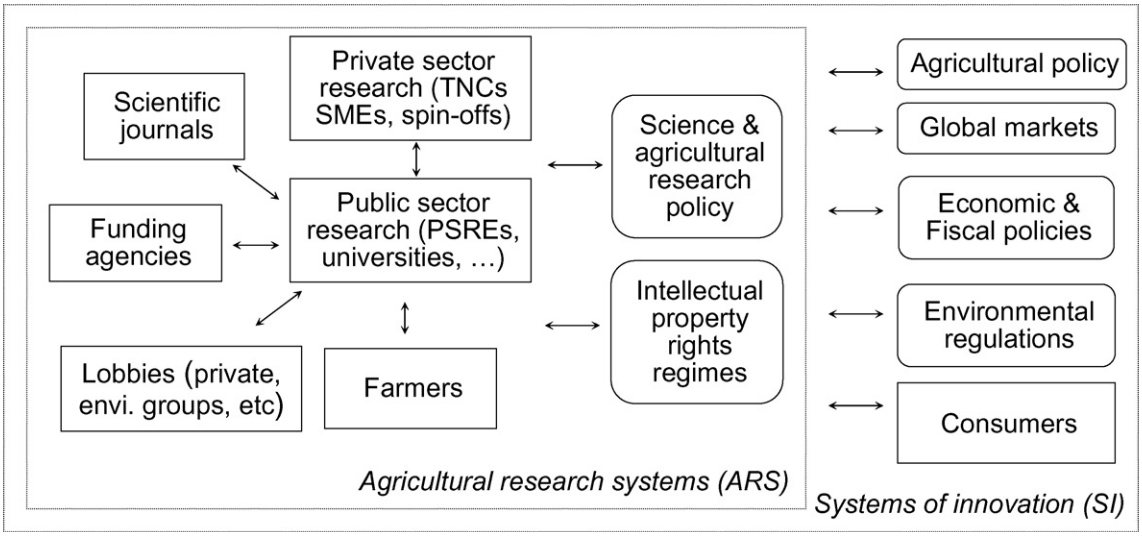

Fig. 1. Agricultural research systems (ARS) are a part of systems of innovation (SI). *Formatting*: Rectangles represent actors. Rectangles with rounded angles represent policies and regulations. Not all interactions are represented. *Acronyms*: TNC, transnational corporations; SME, Small and Medium Enterprises; PSREs, Public-Sector Research Establishments.

and Ruttan, 1985), the factors of technology adoption by farmers (Sunding and Zilberman, 2001) and the public policies and marked-related factors (Tait et al., 2001; Bijman and Tait, 2002). Concerning genetic engineering in particular, Parayil (2003) has demonstrated that the key factors in the emergence of the Gene Revolution (compared with the Green Revolution) were not only the advances of cellular and molecular biology, but also the revolution of information technologies and global economic forces such as the new rules of global finance and free trade, or consolidations and strategic alliances in the agricultural input industry. Russel (1999) focused on the aspects of international political economy that encouraged biotechnologies, specifically the structural power of the US government and American companies.

We maintain however that the analysis is not yet complete for genetic engineering and almost non-existent where agroecological engineering is concerned. Moreover, the advantages of a systematic comparison have not been exploited.

3.1. Theoretical concepts: analysing the current technological regime through an SI approach

Our approach is in the realm of systems of innovation approaches (Lundvall, 1992; Nelson, 1993; Edquist, 1997). The SI approach analyses the components of systems of innovation, their functions and the relationships between components on a national, sectoral or regional scale. We focused on agricultural research systems, which are a large part of the SI that shapes agricultural S&T. ARS are composed of organizations (such as scientists, universities, private companies) and of institutions such as R&D policies (Edquist, 2001). A simplified representation of ARS and SI is shown in Fig. 1.

Within ARS, we identified the factors that influence the choice of technological paradigms and the development of technological trajectories. These factors are 'determinants of innovation': social, cultural, economical and/or political factors that act positively or negatively on the development of technological trajectories (Edquist, 2001). It is the addition and combination of these determinants that collectively forms the technological regime.

We could have made a similar analysis with other concepts. Pestre's concept of 'knowledge production regimes' (2003) encompasses institutions, beliefs, practices as well as political and economic regulations that define the place and role of the sciences. Friedmann (2005) has suggested the concepts of 'food regimes' encompassing broader historical patterns of agricultural production and food consumption. Our specific focus on ARS narrows our scope. Besides, the use of evolutionary economics concepts is coherent with the relevance of this line of thought for agriculture (Marechal et al., 2008).

3.2. Sources and methodology

The sources for the analysis of determinants of innovation are manifold:

- Interviews with scientists and stakeholders in five agrifood chains (wheat, apple, sugar beet, maize, soybean) (20–30 interviews each) in two countries (Belgium and Argentina),
- participant observation of public forums on agriculture, science and innovation in Belgium, France and the UK, as well as in Brussels for EU institutions,
- an analysis of key policy documents such as white papers from public authorities (from the US National Research Council, to the European Commission, to the Food and Agriculture Organization (FAO)).
- A multidisciplinary literature review.

The analysis of the determinants of innovation uses (i) evidence and a few illustrative quotes from our surveys among stakeholders in ARS, (ii) logical reasoning using results and conclusions from published research, and (iii) specific illustrative cases of transgenic plants and/or agroecological innovations.

Our approach was not carried out on a national scale as in many SI approaches. The international division of research has already taken place (Pardey and Beintema, 2001). Russel (1999) emphasises the need to apply the idea of territory loosely and include transnational aspects, even if national differences exist in ARS and SI (Tait et al., 2001). This cross-country, multisource approach is considered useful and valid for agricultural research in both developed and developing countries.

Two assumptions are made. First, 'agricultural research' comprises agricultural as well as biological sciences. Secondly, genetic engineering is closely associated with molecular biology, the basic science on which it rests, even if molecular biology has other goals and is also related to agroecology.

Table 2
Determinants of innovation in Agricultural Research Systems that induce an imbalance between genetic and agroecological engineering.

Categories	Subcategories	Determinants of innovation
(1) Agricultural science policies	Research orientations	Focus on growth, competitiveness and biotechnologies
	Relationships between public & private sectors	Public–private partnerships
		Public–private division of innovative labour
	Influence of lobbies	Imbalance in the power of lobbies
	Media	The media channel public opinion towards a single paradigm
(2) Private sector	Research orientations	Focus on biotechnologies and importance of patents
(3) Public sector	Cultural and cognitive routines (Values and world views of scientists)	Assumptions on current and future agricultural systems
		Assumptions on past agricultural systems
		Assumptions on the nature and value of innovations
	Organization within research systems (rules of the game)	Views of complexity and framing of agricultural research
		Assessment of the performance of agricultural innovations
		Specialisation vs. interdisciplinarity
		'Publish or perish'
		Technology transfer mission: patents, spin-offs and extension

Special attention is intentionally paid to the public sector and to the influence of determinants on agroecological engineering, a field much less explored than genetic engineering. Cultivar mixtures and agroforestry systems are used as examples of agroecological innovations that have already lived up to their reputation, while biological control has an intermediate status.[3]

The results of our analysis sum up all the ARS determinants that together structure the current technological regime. We assume these determinants to be predominant in the choice of technological paradigms and the development of technological trajectories. This does not mean that each determinant is valid in all cases (i.e. present in all research institutions and true for every scientist). Consequently, each determinant must be understood as part of a whole. In fact, the systems approach (Checkland, 1981) assumes that the overall performance of a complex of elements depends not only on the characteristics of each element but also on the interactions between these elements. It is thus the aggregation of the various determinants that matters.

4. Determinants of innovation shape a technological regime that induces an imbalance between genetic and agroecological engineering

The determinants of innovation fall into three main categories: agricultural science policies, private sector research and public-sector research (Table 2). The following sections explore how each determinant affects genetic and agroecological engineering.

4.1. Agricultural science policies

Policies influence technological paradigms in four different ways: choice of research orientations, relationships between public and private sectors, the power of lobbies, and the role of media and lobbies.

[3] Cultivar mixtures are an application of the concept of crop heterogeneity (increasing the genetic diversity in a cultivated field to increase crop resistance to biotic and abiotic stresses). Agroforestry embraces land use systems in which trees are deliberately integrated with crops and/or animals on the same land, usually producing ecological and economic interactions. Biological control is a method of controlling pests and diseases that relies on conservation and/or the enhancement of natural predators and consequently fits the agroecological paradigm. The fact that it is sometimes defined as belonging to agricultural biotechnology should not cause confusion. Biocontrol has an intermediate status in this paper as is often the case, that is the impact of the determinants of innovation on biocontrol are in-between those affecting genetic engineering and those affecting agroecological engineering.

4.1.1. Research orientations: focus on growth, competitiveness and biotechnologies

Science policies are explicitly and increasingly oriented towards growth and national competitiveness. These goals are clearly stated in key policy documents, including the EU 2007–2013 R&D Framework Programme (European Commission, 2005a,b) or the US National Innovation Act (Congress of the US, 2005). Since the early 1980s, biotechnologies have been intimately linked with these objectives (European Council, 1981; National Research Council, 1987). Most countries then implemented specific policies on agricultural biotechnologies such as transgenic plants. These policies are still strongly supported in the United States (NRC, 1998) as well as in the European Union despite the 1999–2004 de facto moratorium on transgenic crops (European Commission, 2002, 2004). International organizations have also supported genetic engineering, though calling for caution and asking for a specific investment in pro-poor technologies, programmes and policies (UNDP, 2001; FAO, 2004).

Genetic engineering benefited from the creation of a broad, favourable environment, which included funds, specific infrastructures (such as the European Molecular Biology Laboratory), and a workforce trained in molecular techniques, a request expressed in early policy documents (National Research Council, 1987). During our surveys, scientists mentioned the fact that molecular biology continued to be important in all EU programmes even after the year 2000s: "*You had to have a molecular biologist in your research project for it to be accepted*". The increased importance of molecular biology has impacted on scientific institutions themselves. An analysis of the recruitment of scientists at the French *Institut National de la Recherche Agronomique* (*INRA*) demonstrates that the share of molecular biologists grew from less than 10% in the 1970s to more than 20% of total job opportunities between 1988 and 1997 (Mignot and Poncet, 2001). In Europe, strong consumer opposition to transgenic plants and the 1999–2004 de facto moratorium on the commercialization of transgenic plants has had a strong negative impact on the development of genetic engineering, with multinationals pulling out of R&D in Europe. EU-supported research on transgenic plants was also partly redirected towards the life sciences linked to human health. Nevertheless, research in genetic engineering continued and the number of field tests numbers rose after the end of the moratorium.

In contrast, agroecological engineering has not been linked to growth and competitiveness goals. Sustainable agriculture only featured more noticeably on research agendas from the late 1990s onwards. "Sustainable Agriculture Research and Education" programmes in the U.S., "agrienvironmental schemes" in the EU and organic farming research programs facilitated the development and the adoption of agroecological innovations. Some agroecological subtrajectories even benefited from the greater interest in molecular biology (biocontrol for the identification of useful biocontrol agents). However, research at the agroecosystem level has not developed as intensely as research at the molecular level. Some research institutions even lost some agronomists and soil microbiologists. Between 1982 and 1988, the substantial increase in funds, faculty and students dedicated to biotechnology in US land-grant universities was concomitant with a decline in the numbers of plant and animal breeders (Hess, 1991).

4.1.2. Relationships between the public and the private sectors

Two trends in the relationships between public and private research have influenced the technological paradigm: the increased influence of industry through public–private partnerships, and the division of the innovative labour between public and private entities.

4.1.2.1. Public–private partnerships. The promotion of public–private partnerships (PPP) is now explicitly part of the missions given to public-sector research establishments PSREs, as a mean to transfer technology and knowledge (Tait et al., 2001). Examples of PPP in the realm of biological and agricultural sciences include the well-known alliance between Novartis and the University of California to support basic agricultural genomics research (US$ 25 million over 5 years) or plant genomics platforms such as the French initiative *Genoplante*.

Genetic engineering has benefited more from PPPs than agroecological engineering, because PPPs were only launched on technological trajectories in which private firms had an interest. (Note that firms have invested more in modern agricultural biotechnologies than in agroecological innovations in the last three decades, see Section 3.2.) Moreover, PPPs have had an indirect but more profound impact: a change in the culture of science. A key finding of an external evaluation of one of these large PPPs – the University of California-Novartis agreement – found that administrators and university scientists who participated in the partnership tended to define the public good as research that leads to the creation of commercialized products, narrowing the definition of the public good towards private goods (Busch et al., 2004). As Levidow et al. (2004) puts it, “even a small proportion of industry funding can influence overall research priorities: the tail can wag the dog”. This trend is favourable to transgenic plants but unfavourable to agroecological innovations with a public good characteristic. In the end, PPPs could induce a redirection of public funds towards the areas of research leading to these partnerships PPPs if they are considered likely to have a positive effect on economic growth (Pew Initiative on Food and Biotechnology, 2003; Food Ethic Council, 2004).

Another trend in public research–industry links has been privatization. Direct privatization of research infrastructure and resources has been an important feature of reorganization only in the UK. Indirect privatisation happened nevertheless in many countries through by giving private research institutes access to public funds, or through the “industry capture of research programmes”, e.g. through the increased presence of industrial representatives on committees establishing research priorities (Alston et al., 1998b, 2001). This indirect privatization, like PPPs, favours the innovations that attract the private sector, at the expense of innovations of a public good nature (whose benefits are not exclusively appropriated by the farmer, but are of wider public value as they produce large externalities). These trends are in line with the analysis of industry’s increased influence on public science (Slaughter and Leslie, 1997).

4.1.2.2. Public–private division of innovative labour. There is a ‘division of innovative labour’ (Arora and Gambardella, 1994) between the various public and private research institutions in the agricultural and biological sciences. Public-sector research focuses on basic research while the private sector focuses on applied R&D.

Genetic engineering has benefited a lot from this division of innovative labour, as research on this technological paradigm occurred at all levels (basic, applied and development). An analysis of US patents issued between 1975 and 1998 in the field of biological sciences applied to plant agriculture demonstrates that universities undertake the initial research that contributes to the evolution of technological trajectories and yields the most original and most general work, while start-up companies specialise in turning basic research into applied innovations and large corporations concentrate on later developments (Graff et al., 2003; Graff, 2004). More than 70% of US publications cited in agricultural biotechnology patents are authored by US university researchers, a good measure of the importance of public science (Xia and Buccola, 2005). In other words, biotech industries depend on public science much more heavily than other industries (McMillan et al., 2000). Contrariwise, the division of innovative labour is not a positive factor if all research stages are not shared out, for instance if the private sector does not invest in applied research and development, which is the case of many agroecological subtrajectories (see Section 3.2).

4.1.3. Imbalance in the power of the lobbies

The analysis of the influence of lobbies (providers of agricultural inputs, consumer groups, environmental conservation groups) is an integral part of the SI approach, since they influence strategic choices and thus, technological paradigms (Edquist, 1997).

Genetic engineering has received the backing of strong industrial platforms such as Bio in the US or Europabio in the EU Their lobbying has considerably influenced public policies such intellectual property rights (IPR) regimes in the framework of the World Trade Organization, as well as on research framework programmes at the European Commission (Balanya et al., 2003; Parayil, 2003). However, they did not manage to stop the 1999–2004 *de facto* EU moratorium on transgenic crops.

The activity of green lobbies on agroecological engineering is not as straightforward. Environmental NGOs such as Greenpeace or the Soil Association have put more energy into banning transgenic crops or securing strong regulations than into promoting a research agenda for alternative technological paradigms such as agroecological innovations. However, slowing down one trajectory does not automatically result in support for another. Remember that the few scientific organizations that back a stronger research agenda on agroecology (Union of Concerned Scientists, 1996; European Science Social Forum Network, 2005) have significantly less clout than mainstream scientific organizations that support genetic engineering (Royal Society et al., 2000).

4.1.4. The media channel public opinion towards a single paradigm

The simplified approach characterizing the mainstream media favours a binary approach concentrating on the benefits and risks of genetic engineering, for better or worse. The stress on potential risks is a drawback, yet the coverage of ambitious possible outcomes has maintained trust in the technology’s potential. Media have not adopted thinking on technological choices that would have discussed the comparative advantages of transgenic crops and their alternative options. Between 1981 and 2008 the archives of *The New York Times* contain, for instance, 2696 references to ‘genetic engineering’ against 3 for ‘agroecology’, 7 for ‘agroforestry’ and 0 for ‘cultivar mixtures’ (The New York Times, 2008). Moreover, agroecological innovations, when considered, are usually presented as innovations for organic agriculture, not as possible agricultural practices in the future. The media’s stand is of great importance, give the power they wield over public opinion. As communication theorist Bernard Cohen observed in what became a widely accepted communication theory: "*the press is significantly more than a purveyor of information and opinion. It may not be successful much of the time in telling people what to think, but it is stunningly successful in telling its readers what to think about*" (Cohen, 1963). The public's attention is thus drawn to the risks and benefits of genetic engineering, not to the alternatives such as agroecological engineering.

4.2. Private sector research

The private sector is an increasingly important actor in agricultural research, accounting for roughly one-third of global agricultural research spending (Pardey and Beintema, 2001). This share rises to 50% in OECD countries, where the growth of private R&D is three times that of public research (Alston et al., 1998a). In capitalist market economies, innovation is a tool to generate higher revenues and secure competitiveness, a matter of survival for most private companies. However, private companies do not invest equally in all technological trajectories. R&D strategies rely on the possibility to secure sufficient future revenues from R&D spending. Consequently, private companies focus on innovations that can be protected by patents or other forms of IPR regimes.

A key event gave transnational companies the green light for huge investments in genetic engineering. In 1980, the United States Supreme Court decision in *Diamond v. Chakrabarty* allowed patenting on microorganisms, and this was later extended to plants (National Research Council, 2002). Companies such as Monsanto or Novartis (now Syngenta) then made strategic decisions to orient their R&D activities towards genetic engineering in the 1980s, and acquire the appropriate companies throughout the 1990s. Between 1976 and 2000, firms invested more in modern agricultural biotechnologies than in other patentable biological innovations, such as biocontrol of pests and diseases (Heisey et al., 2005). Consequently, three out of four US agricultural biotechnology patents are in the private sector today (Graff et al., 2003).

Agroecological innovations have not benefited from this new regime of intellectual property rights. Only a few patentable agroecological innovations attracted private actors, such as biological control (which leads to patents on methods for rearing biocontrol agents). The private incentives for agroecological research are actually limited as private companies are unable to capture all the benefits resulting from these innovations (Sunding and Zilberman, 2001). For instance, innovations in agroforestry systems can hardly be patented, they are hard to promote as their benefits are in the very long-term (wood is a long-term production) and their benefits are to a large extent public goods (positive environmental externalities such as carbon sequestration or biodiversity). Consequently, agroecological innovations such as agroforestry or cultivar mixtures have mainly relied on the public sector for their development.

4.3. Public-sector research

The internal organization of the public agricultural research sector (universities, national and independent not-for-profit research institutes), as well as cultural and cognitive routines, are also part of the technological regime.

4.3.1. Cultural and cognitive routines (values and world views of scientists)

Cognitive and cultural rules or routines are assumptions scientists and experts frequently make. They make them look in particular directions and not in others (Dosi, 1982; Nelson and Winter, 1982). It has been acknowledged for long that values and world views interfere with science as well as with risk assessment, expertise and public policies (Jasanoff, 1990; Lacey, 1999; Stirling, 1999). Assumptions on current, future and past agricultural systems, and assumptions on the nature of innovation, generate an imbalance between the two technological paradigms.

4.3.1.1. Assumptions on current and future agricultural systems. A common assumption made by scientists about the current modern agricultural systems is that they only require small adaptations. Problems such as pesticide risks are acknowledged, but the validity of the model in itself – monoculture, reliance on a high level of external inputs such as fossil fuels – is rarely questioned. Thinking on agriculture remains close to the industrial approach that has characterized agricultural sciences for more than a century (Bawden, 1991), complemented when possible by some soft ecological concepts such as integrated pest management (IPM).

As for the future, scientists mainly think in terms of the *most probable* future agricultural systems, not the *most desirable* future systems, i.e. they seem to forecast future agricultural systems by integrating the most probable economic and political trends. These trends are the globalization and liberalization of agricultural commodity markets, two trends that pushes all regional agricultural systems into global competition (Cerny, 1997), and the strengthening of the strategies of the dominant actors in agrifood transformation and retailing (Goodman and Watts, 1997). As these trends exacerbate economic pressures on farmers, the pursuit of input-intensive approaches is thought to be the most probable evolution. Many scientists frame their research around these constraints and behave as if global warming and the rising cost of energy did not demand major policy shifts (Kirschenmann, 2007) or as if there was no alternative to the mainstream economic trends (Patel, 2007).

Genetic engineering fits into these expected trends: it does not entail many changes in current farming systems, such as monoculture. It only uses different types of seed, inputs (herbicides and insecticides) and management schemes and is thus seen as 'potentially transferable' to farmers.

Innovations and systems closest to the principles of agroecology face the opposite situation as they challenge the fundamentals of the current agricultural system, such as monoculture and crop protection relying mainly on external interventions. Many scientists do not explore these agroecological innovations because "*it goes against the flow*", as a scientist explicitly stated during an interview, when asked why cultivar mixtures were not being researched to create systems resistant to fungal diseases. Scientists and stakeholders refer to current social and economic barriers impeding the use of some possible innovations by farmers today to justify the research deficit. Current barriers are seen as permanent immovable obstacles. As a result, some agroecological innovations are considered to be 'theoretically valid' but 'not feasible' in modern agricultural systems, as they 'go against the flow'. The attitude towards genetic engineering is different: the current opposition of consumers in Europe is not seen as an immovable obstacle.

4.3.1.2. Assumptions on past agricultural systems. Past agricultural systems are rarely seen as sources of insights for innovation in mainstream agricultural science, where modernization remains an important leitmotiv. This is a small issue for genetic engineering, which has little need of insight from past agricultural systems. On the contrary, agroecology values past systems as a source of insight for the improvement of current systems. Examples or 'rediscovered' systems are subtle combinations of rice terraces and agroforestry systems in Madagascar, rice–fish systems in East-Asia, Andean waru-waru ridge fields that control drought and frost or Mesoamerican milpa-solar cropping systems in Mexico (Esquinas-Alcázar, 2006).[4] Such systems are seen as a 'return to old times', worthy of curiosity, but not of real academic interest. Consequently, research into indigenous knowledge and traditional

[4] These past agricultural systems have today been recognized as *Globally Important Ingenious Agricultural Heritage Systems* (GIAHS).

systems has until recently remained a weak area of agricultural research (IAASTD, 2008).

4.3.1.3. Assumptions on the nature of innovation (biotechnological and agroecological innovations. Scientists make two important assumptions on the nature and value of innovations that generate an imbalance between technological paradigms.

The first difference relates to the nature of innovations. Molecular biology and genetic engineering are seen as 'breakthrough' scientific discoveries, which lead to fundamental- or radical innovations. On the contrary, agroecological innovations are taken as 'incremental' innovations, despite agroecology's record of success stories that include the restoration of traditional Incan terracing systems, that increased productivity by as much as 150% (Parrott and Marsden, 2002), wheat-poplar agroforestry systems that produce as much 'grain + wood' output on 1 ha as 1.3 ha of separate monocultures (SAFE, 2005), and barley cultivar mixtures that reduced the incidence of powdery mildew, and fungicide use by 80% on 350,000 ha in East-Germany between 1984 and 1990 (Vallavieille-Pope, 2004).

Genetic engineering is also seen as a provider of 'total' solutions while agroecological engineering would only offer 'partial' solutions that must be completed by other strategies. The reality is far from this simplistic assumption: plants genetically engineered for resistance to diseases or drought are expected to have an improved, but not complete resistance. Rather than their true potential to solve problems, the 'low-technology' aspect of agroecological innovations is a possible cause of the scant interest they receive in ARS. As Wolfe, a prominent scientist working on cultivar mixtures puts it: "*Is it just too simple, not making enough use of high technology*?" (Wolfe, 2000).

The second difference is the widely shared belief that genetic engineering is of universal value, a belief that does not exist in agroecology (Lacey, 2002). While agroecology would only be of value for some problems and in some regions, genetic engineering would be able to solve all problems in all places. This major assumption in favour of genetic engineering is supported by three major arguments.

Firstly, many scientists consider agroecological innovations to be innovations 'for organic agriculture' because agroecology and organic agriculture share common agroecological principles. Research funding is low because organic agriculture is considered a niche market innovation and because of the mainstream view that organic agriculture is unable to feed the world, an opinion disproved by recent research (Badgley et al., 2007; FAO, 2007).

Secondly, many scientists reject agroecological innovations as being neither true research nor 'development'. Nothing could explain this better than the actual words of a scientific adviser for a public authority responsible for agricultural research funding; interviewed as part of this research: "*It is very difficult to finance a research that is not anymore a* '*real one*', *i.e. when the scientists have already put into evidence all the scientific laws they could put into evidence, even if that research project needs a large-scale validation. These projects should systematically go to the Development department but it's hard and it rarely happens: it seems too* '*research*' *for the Development department*."

Thirdly, some agroecological innovations are dismissed because their current record of results for commercial real-scale applications is considered too low. This is clear in the case of elicitors of induced resistance, a new possible way to protect crops by inducing plant defence mechanisms. While the early fundamental research on this subtrajectory dates back to the 1940s (Kuc, 2001), research applied to commercial crops has been much more recent. For instance, the screening of the thousands of possible molecules effective for apple diseases truly started in the 2000s, yet the absence of rapid positive results led many stakeholders to conclude that elicitors were not a solution, while they should actually be considered as a fairly new trajectory, just like transgenic disease-resistant apple trees (Vanloqueren and Baret, 2004).

The fact that the value of agroecology has not been universally acknowledged may also arise from the absence of a strong integrated prospective vision of agroecological engineering, which would take into account the possible synergies between the different agroecological subtrajectories. Such a vision could lead to breeding wheat cultivars designed to be most productive in cultivar mixtures grown in agroforestry systems which would themselves include beetle banks, and finally be protected by the mass release of aphids for pest biocontrol.

We may conclude from this analysis of cultural routines that scientists have a biased approach to the two technological paradigms analysed in this paper. Genetic engineering is recognized as a technological paradigm and trajectory while that is not the case for agroecological engineering. The scientist's perception of genetic engineering is dynamic: genetic engineering has produced results in the past, it does today and it has potential for the future: it is a technological paradigm and trajectory. The scientist's view is static when it comes to agroecological engineering: scientists acknowledge that agroecology exists, but they do not consider its innovative possibilities in the same light as those of genetic engineering. This 'variable geometry' approach is in total contradiction with 'sound science that should have a balanced vision of the two paradigms, as both make sense and make science as shown in Section 1.

4.3.2. Organization of research systems

Five organizational aspects influence technological paradigms and trajectories: the different views of complexity and the framing of agricultural research, the assessment of the performance of agricultural innovations, the specialisation of research, the publication pressure, and the technology transfer mission.

4.3.2.1. Views of complexity and the framing of agricultural research. Science deals with complexity by nature. Both molecular biologists and agroecologists agree that living beings and ecosystems are complex systems. Yet the two paradigms deal with different types of complexity.

Molecular biology and genetic engineering are about complexity at the cell and the gene levels. The technical and technological developments of the three last decades have greatly helped scientists to deal with this type of complexity. Computers process more and more data while DNA sequencers can sequence longer strands of DNA more quickly. These developments have allowed a 'taylorization' of research. Scientists in this field now compare their institutions in terms of thousands of Mb (mega base pairs) per day.

Agroecological engineering, on the other hand, is about complexity up to the ecosystems level. The main approach is a systems approach, which does not fit the laboratory realms as well as a reductionist approach. A good example of this complexity is agroecological research on the improvement of coffee groves grown under high-canopy trees in Central America; the improvement involved the identification of the optimal shade conditions that could minimize the entire pest complex and maximize the beneficial microflora and fauna while maximizing yield and coffee quality (Staver et al., 2001).[5] New software and tools also helped these analyses, but such highly context-dependent research is not open to the standardization processes that were so useful to the development of genetic engineering. Thus agroecological innovations are thought to be too complex to be dealt with, which could seem paradoxical given the complex technologies used in genetic engineering.

[5] Variables include light intensity and rate of humidity, pest complex, diversity of trees and coffee cultivars, shade management, altitude, climate and soil.

Time and size requirements for research on each paradigm also differ widely. The transposition of a transgene into a host plant can be detected by easy means in the lab within days, and lead to scientific discoveries that are published in renowned scientific journals. In contrast, sound research on a number of agroecological subtrajectories requires large-scale and long-term on-farm experiments. Proving the positive effect of rice cultivar mixtures on the prevalence of an important disease involved above 3000 ha of Chinese rice fields, as scale affected results (Zhu et al., 2000). The productivity assessment of wheat–walnut agroforestry system takes years from the planting to publishable results, a requirement that poorly matches the short time frame of research grants (Auclair and Dupraz, 1999).

4.3.2.2. Assessment of the performance of agricultural innovations. Scientific and methodological reductionisms also involve greater focus on the assessment of direct, local and short-term impacts, along with underestimation or neglect of the indirect, global or systemic and long-term impacts of agricultural systems and innovations. Stress is easily laid on measurable variables such as gross yield rather than those variables that are much more complex to measure such as sustainability and externalities. This encourages scientists and innovators to focus on yield rather than economic optimum, on monocultures rather than multiple cropping systems. This influence can be traced to the econometric methods of calculating rates of returns on investments in agricultural research, which only take into account one objective (total net benefits, or growth), instead of taking into account externalities and multiple socioeconomic and environmental objectives (Alston et al., 1995; Vanloqueren and Baret, 2008).[6]

Classic agricultural performance assessments are favourable to genetic engineering. The benefits of transgenic plants, usually grown in monocultures, are local and direct, and are consequently taken into account. On the contrary, classic performance measurements hinder agroecological engineering, particularly the subtrajectories with strong positive environmental or economic externalities. For instance, agroforestry systems are also carbon sinks, they help to improve soil fertility and biodiversity, while also bringing new revenues to farmers.

4.3.2.3. 'Publish or perish' constraints and the organization of scientific publications. Scientists in academic institutions aim to improve scientific knowledge and share discoveries through publications, which are non-market incentives to value priority in scientific discovery. Yet the different technological paradigms lead to dissimilar publication trends and impacts. The difference of academic prestige between the two technological paradigms may be grasped by a simple bibliometric analysis of some of the most appraised scientific journals: genetic engineering features roughly a hundred times more than agroecological engineering in *Nature*, *Science* and *The Proceedings of the National Academy of Sciences*.[7] In general, research representative of genetic engineering is published in scientific journals with impact factors (IF) as high as 29.3, while agroecological research is published in journals with IF ranging from 0.4 to 4.5.[8]

Genetic engineering and molecular biology are in fact perfectly adapted to the current publishing constraints. Firstly, the most appraised scientific journals focus on the smallest levels of organization in life (the plant, the cell and the molecular level). Secondly, the taylorization of research favours the division of research into a handful of publishable results, from the identification of a particular gene, to the method of transposition into a host plant, to the assessment of its activity in the host plant. Agroecologists also publish parts of their work separately while the exact goal of agroecology is to encompass an agroecosystem as a whole. Innovations in the field of agroforestry take years before producing any publishable results. Scientists working on such agroecological trajectories collectively publish fewer papers.

With the growing importance of international rankings and formal research assessment procedures (as in the U.K.), the difference in 'publication productivity' may become an incentive to hire more molecular biologists in the future, as they contribute more than agroecologists to the global competition for highest rankings. This will, in turn, influence the career choices made by young scientists.

4.3.2.4. Specialisation vs. interdisciplinarity. Genetic engineering thrives with the growing specialisation of science and the taylorization of research in biotechnology laboratories. It calls for interdisciplinarity, yet one that remains inside the realm of a restricted number of natural sciences. The scientists involved share common cultures, languages, methods and techniques. In contrast, agroecological engineering requires the greater integration of agronomical, ecological, social and economic dimensions (Altieri, 1989, 1995). Academic barriers to interdisciplinarity are therefore obstacles to the development of agroecological trajectories (Dalgaard et al., 2003).[9] Moreover, the low value given to social sciences in ARS is also an impediment, whereas they could help identify and create institutional innovations that improve knowledge-sharing processes, which are vital to the development of agroecology (Uphoff, 2002).

4.3.2.5. Technology transfer mission: patents, spin-offs and extension. Another mission of agricultural-related public-sector research establishments (PSREs) is to transfer knowledge and technology from basic to applied research to the private sector. To do so, PSREs are expected to file patents on their exploitable results and launch spin-off companies (Tait et al., 2001). However, technological trajectories are not equally suited to generate patentable results (see Section 3.2). Possibilities to create spin-offs are also unequal. So universities that rely increasingly on non-public money are encouraged to engage in subtrajectories that lead to patents and spin-offs.

Extension or technology transfer to farmers, is another mission of PSREs and other dedicated centres. Its explicit objective is to improve the situation of farmers and help them face new challenges such as increased international competition and environmental issues. While this may seem a positive factor for both paradigms, these organizations often concentrate on technologies that can be

[6] Advances in environmental economics and ecological economics are yielding new and better-adapted methods, which are nevertheless not yet widely known in ARS and extension services.

[7] A simple keyword search for genetic engineering found 358 papers, while a similar keyword search for agroecological engineering found only one paper, 2 papers for crop mixtures and 2 for agroforestry. ISI Web of Science, ISI Web of Knowledge, October 25, 2006. Databases = SCI-EXPANDED, SSCI, A&HCI; Timespan = 1987–2006.

[8] Journal Citation Reports and ISI Web of Science, ISI Web of Knowledge, November 15, 2006. Technological trajectories were first defined by keyword lists, then the scientific journals with highest publication records for these keyword lists were selected and their IF checked. Illustrative examples are *Nature Biotechnology* (22.7); *Plant Physiology* (6.1), *Agriculture, Ecosystems & Environment* (1.5), *Agroforestry Systems* (0.7). Another way to look at the same thing is to analyse IF of the 20 most influential journals (those with highest impact factor) in ISI categories representative of each trajectory. Similar results are found. Publications most representative of genetic engineering are published in the following ISI categories of scientific journals: biotechnology and applied microbiology, plant sciences, biochemistry & molecular biology. The 20 most influential scientific journals in these categories have an IF rating of between 2.7 and 33.4. Publications most representative of agroecological engineering are agronomy, agriculture/multidisciplinary, ecology and environmental sciences. With the exception of the category 'ecology' (IF between 3.3 and 14.9), most influential journals have an IF of between 0.3 and 5.3.

[9] These barriers are cultural and organizational: securing research grants, going on exchange programmes, publishing, gaining recognition, securing a job, or being promoted (Bauer, 1990; Nissani, 1997).

of direct use to farmers (new cultivars, choice of best fungicide mixtures or optimal timing of spraying), with an ensuing improvement and strengthening of the dominant agricultural system (modern input-intensive monoculture). This is mainly a positive factor for genetic engineering, as transgenic crops suit this system. Agroecological innovations on the other hand do not become a priority, as they do no fit into the existing agricultural system and require structural changes (such as breaking away from large-scale monocultures).

In a word, the overall organization of research systems is broadly more in favour of genetic engineering than agroecological engineering.

5. Emergent properties: path dependence and lock-in

Current research orientations are not only influenced by one or several of the determinants of innovations analysed above. They are also shaped by two other processes that can be described as systemic emergent properties of agricultural research systems: path dependence and lock-in.

Path dependence has been suggested to explain the stability of sociotechnical systems. Among several technologies that perform similar functions and compete for adoption by economic agents, one technology may become dominant, even though it may have an inferior long-run potential (David and Arthur, 1985; Arthur, 1989). This process is 'path dependant' as the initial conditions may greatly influence the success of the dominant technology, particularly when increasing returns occur.[10] This process is self-reinforcing and may lead to a technological lock-in situation in which the dominant technology excludes competing and possibly superior technologies (Liebowitz and Margolis, 1995).

The existence of path dependence and lock-in processes has been observed in agriculture, in such sectors as pest control strategies and breeding (Cowan and Gunby, 1996; Wilson and Tisdell, 2001). While the concepts of path dependence and lock-in are generally used to analyse the adoption of competing innovations by end users, they are used here to help understand the adoption of competing technological paradigms by scientists and by agricultural research systems.[11]

Plant breeding is one of the rare sciences where the importance of past research efforts is well understood. It has for instance been shown that wheat varieties launched in the USA in the early 1990s relied on varieties developed or discovered as long ago as 1873, with over 36% of the varieties incorporated existing before 1940 (Pardey and Beintema, 2001). The concept of 'knowledge stocks enables more precise quantification of the importance of past research efforts. Knowledge stocks are money measures of the stocks of scientific knowledge (Adams, 1990). US scientists found out that the accumulated stock of agricultural knowledge in the USA in 1995 (from 1850 onwards) was 11 times larger than the amount of agricultural output produced during the same year (Pardey and Beintema, 2001). This means that "*for every $100 of agricultural output, there existed a $1,100 stock of knowledge to draw upon*". These observations are of the utmost importance as they demonstrate that modern agricultural systems rely on a wide scientific base, not only on public subsidies, as generally acknowledged.[12]

Past technological paradigms and their associated trajectories have thus profound and lasting effects on ARS, since current innovations have their roots in past strategic decisions and research efforts. Past science policies were shaped by productivist objectives that were and still are more favourable to genetic engineering than to agroecological engineering.

The accumulation in time and the continuous interactions among all the determinants of innovation shape the current technological regime, but have also created a technological and institutional lock-in situation that severely hinders or stops the development of one of the technological paradigm, in this case agroecological engineering, though both paradigms make sense and make science, as seen in Section 1.

Genetic engineering, while a breakthrough innovation, was not locked-out. It fitted the main scientific approach (positivism and reductionism) as well as the technological regime shaping agricultural systems for decades (current transgenic plants have a 'technological coherence' with the development of pesticides) and finally, with the larger political and economic trends that has reshaped the global economic system during the three last decades (Parayil, 2003; Patel, 2007). Agroecology has stayed however on the margins of the agricultural sciences, as it is distant from the main scientific approach as well as from the technological regime and the larger economic and political dominant trends. Its development has long been too limited to lead to significant increasing returns ('learning by doing', 'network externalities').[13]

6. Discussion: breaking out of lock-in situation in agricultural S&T

The existence of a lock-in situation in agricultural research systems is not only of theoretical importance: it has consequences for public action.

Lock-in situations justify public intervention if science is understood as a public good. As put forward by Callon and Bowker (1994), science is a public good which must be preserved at all costs because it is a source of variety and of new global developments ('states of the worlds'), and because the market would lead to irreversible situations without it. The sources of irreversibility are numerous because a change of scientific trajectory implies high switch-over costs (Geels, 2004). Scientists have been educated in a particular way and have acquired specific competencies that enable them to be best in some domains and not in others. The cost of moving from one research theme to another is too high (knowledge, reputation, networks, access to research grants). Research centres have also invested in infrastructure and machines that need to be paid off, and give a comparative advantage for one or several very specific scientific areas. These switch-over costs favour incremental progress along an established technological trajectory rather than a change of paradigm and trajectory.

The issue is thus how to break out of this lock-in situation, as incremental progress is just not enough. Agroecological innovations hindered by the lock-in have been analysed as crucial for our societies, especially in the context of climate change and the need for sustainable agriculture (see IAASTD in Section 1).

The practical ways to systematically reduce the imbalance between the two paradigms are beyond the scope of the paper. We have briefly discussed three aspects that are the key to the necessary shift requested by the IAASTD recommendations: 'fair'

[10] Increasing returns are summarized by Callon and Bowker (1994): the more a technology is produced and offered, the more it becomes worthwhile for the supplier to produce it and for the user to consume it. Increasing returns to adoption may be of three types: scale economies, learning economies ('learning by doing', performance is improved as specialized skills and knowledge accumulate through experience) and adaptive expectations (increasing adoption reduces uncertainty among producers and users) (Unruh, 2000).

[11] This application of the concepts can be best understood by reading the preceding paragraph and replace 'technologies' by 'technological paradigms'.

[12] Public support to farmers represents 29% of farm receipts in OECD countries (OECD, 2006).

[13] On increasing returns, see Callon and Bowker (1994), pp. 407–408.

forecasting, the importance of 'niches' in innovation policies, and issues of complementarity between technological paradigms.

Firstly, 'fair' forecasting exercises need to be performed in order to explore the potential contribution of the two paradigms to solve current and future challenges. Very few analyses have been made to forecast where our agricultural systems could be in 10 or 20 years if S&T policy and agricultural policies massively promoted agroecological innovations, while forecasting on agricultural biotechnologies have been plentiful (Strategy Unit of the Cabinet Office, 2003; Reiss and Strobel, 2003).

Secondly, innovation policies must take into account the importance of niches and the true value of agroecological innovations in order to face the challenges of the global climate change. Innovation niches are locations where it is possible to deviate from the rules of the existing technological regime (Geels, 2002, 2004). These niches have a crucial role in the stimulation of radical innovations to counterbalance the consequences of path dependence and lock-in. Some innovations, wind turbines for example, may have an initial low performance, but that their development in a niche brings about their improvement through learning processes, technical developments, and/or adapted public policies. Agroecological innovations such as cultivar mixtures or agroforestry systems are precisely radical innovations that have both emerged in protected spaces (subsidised schemes, research programmes and the like). Niches are also crucial because they serve as laboratories that prepare us for the wider changes that are occurring or will occur. Today, climate change and the rising cost of energy are key elements that prove that the current technological regime is unfit for current and future needs (Kirschenmann, 2007). These challenges justify direct support to innovation niches, not to speak about fundamental changes in the dominant technological regime.

Thirdly, the issues of complementarity and competition between the two paradigms must be faced. Innovations from both paradigms are supposedly complementary (Conway, 1999). It is expected for instance that drought-tolerant transgenic plants could be used within agroecological systems designed to maximize resilience to climate extremes. However, if technological trajectories are to be used together in the future, their complementarity needs to be widely recognized and collectively thought out. This is not the case today. Proponents of genetic engineering strongly deny the potential of agroecology to feed future generations. Many agroecologists, on their side, object to genetic engineering, follow a rigorous precautionary approach and argue that classic and marker-assisted breeding are sufficient. These scientists postulate that the right model for agriculture is ecology.[14]

Another aspect of this expected complementarity is the uncertainty about the alleged universal value of genetic engineering. Twelve years after the first commercialization of transgenic crops, the second generation of transgenic plants has not materialized: herbicide-resistant and *Bt* insect-tolerant transgenic crops still make up 99% of the transgenic crops acreage. Moreover, there is great uncertainty about the possibility that 'sustainable' transgenic plants will be developed in the future because of scientific obstacles and structural aspects of the biotech industry (Hubbell and Welsh, 1998).

Coherent complementarity would require, let alone the acknowledgement of the existence of several innovation pathways, clarification on the likely developments in both trajectories, an identification of long-term risks associated with genetic engineering, a shared definition of agricultural sustainability, and a shared vision of future agrifood systems as well as political economy choices.[15]

7. Conclusions

The concepts of technological paradigms and technological trajectories are useful to explain and analyse important trends in agricultural science and technology (S&T) at a time when fundamental shifts in agricultural S&T are increasingly recommended. Genetic and agroecological engineering (agroecology), two of these trends, can be analysed and compared with these concepts.

The process by which one paradigm is favoured over the other is the result of the interactions between many factors, and not a deliberate and planned movement. The system of innovation (SI) approach is powerful to demonstrate how agricultural research systems are a selection device that influences S&T choices. It leads to an in-depth analysis of all the determinants of innovation (factors influencing S&T choices) ranging from orientation of science policies to scientists' cultural and cognitive routines. The interactions among these determinants shape a technological regime. Genetic engineering, a technological paradigm that is well suited to scientific reductionism, is more successful in this technological regime than agroecological engineering, a paradigm that questions mainstream approaches within agricultural research. The development of agroecological innovations is clearly impeded, while their importance for sustainable agriculture and climate change has been clearly established in recent international reports such as the recent international assessment of the role of agricultural S&T for development (IAASTD).

Our analysis contributes to strengthen the relevance of the evolutionary line of thought (evolutionary economics) against the neo-classical approach for agriculture-related issues.

The existence of path dependence and lock-in situations in agricultural research legitimizes public intervention. In other words, a global environment favourable to agroecology must be created if the recommendations of the IAASTD are to be implemented. This means not only a more balanced allocation of resources in agricultural research, but attention to the larger framework that influences S&T choices.

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[14] As put by Weiner (2003), "*Ecology is a relatively young science that cannot yet deliver answers to many of the questions agricultural researchers are asking. But this does not mean that the answers can be found elsewhere. One cannot solve traffic problems through the engineering of automobiles alone. One needs to use traffic engineering, even if traffic engineering is not as highly developed as automobile engineering*".

[15] The two technological paradigms have very different visions of the desirable socio-economic development for the future. A large share of agroecologists challenge economic globalization, agricultural trade liberalization, and the current view of what a productive and sustainable agricultural system is (The International Commission on the Future of Food and Agriculture, 2003). Agroecologists privilege alternative food systems operating at a regional scale or based on closer farmer–consumer relationships, or product networks that mobilize localized resources and have strong identities (Goodman and Watts, 1997; Whatmore and Stassart, 2003; Allaire and Wolf, 2004).

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