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An evolutionary approach to technological innovation in agriculture: some preliminary remarks

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Abstract

This article proposes an interpretation of the process of technological innovation in agriculture. We begin with a criticism to the idea of agriculture as a particular environment in economic analysis. We argue that some dynamic concepts from economics of innovation, especially as seen by the evolutionary literature, can be used as an adequate theoretical reference to study innovation in agriculture. We then suggest an interpretation in terms of technological trajectories in order to explain the complexity of the technological regime in agriculture. Finally we discuss the present stage of transformation in this technological regime and the perspectives of the arising new trajectories.

1. Introduction

The process of innovation in agriculture has received much attention by economists since the 60s. Borrowing Hicksian concepts, the induced innovation literature has been the most important item in the economics of technical change in agriculture. In the 70s, some criticisms on such theories were carried out by left wing economists, more based on social and political evidence of unfairness and uneven income distribution than on economic arguments. Many Marxist authors kept a critical attitude, concerning the obstacles to capitalist development due to land rent and the supposedly rigid natural conditions in the agricultural activities. For them, technological innovation is determined by the logic of capital, in order to overcome these 'barriers'. From the economics side, many empirical studies were made dealing with the dynamics of agriculture innovation focusing on the strategies of upstream industries – like fertilizers, seeds, pesticides and agricultural machines. To some extent the sociological approach prevailed over the economic one, stressing the perverse effects of the innovation diffusion process.

However, it is very doubtful that one could build up useful analytical tools to analyse the dynamics of technological innovation in agriculture without suitable concepts related to a general economic approach to the innovation process in capitalist economies. Some useful references to this purpose can be found in Neo-Schumpeterian and evolutionary approaches, especially papers focusing on intersectoral technological transfer, such as Pavitt's contributions that classify agriculture as a supplier dominated sector. Other references can be found in papers by Rosenberg and Nelson and Winter.

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We argue that the concept of technological trajectories can be extended to the economics of agriculture, since to consider agriculture as a supplier dominated sector is not enough. Even the user–producer approach, well applied by Lundvall (1988) and others to particular environments, may be taken as part of a more general approach.

In this paper we intend to address the following questions: are particularities in the innovation process in agriculture strong enough to justify a specific theory? If not, could the Neo-Schumpeterian approach be fruitful to explain such process?

To answer these questions we adopt the following structure in this paper: (1) a critical discussion focused on theoretical foundations of innovation and sectoral analysis; (2) an item discussing the technological trajectory concept in agriculture; (3) finally, from this theoretical standpoint, we intend to suggest how to study the present empirical evidence of transformation in the technological regime in agriculture.

2. Patterns of innovation in agriculture: elements of a sectoral analysis

Following the Neo-Schumpeterian theory of competition and its microeconomics analytical framework, static equilibrium analysis is considered as inadequate to deal with the essentially dynamic features of the capitalist economy and is replaced by the analysis of endogenous industrial dynamics, where equilibrium is neither a necessary outcome, nor a methodological requirement.

Competition is in the centre of the theory. It is taken as an active process of creating new competitive advantages, reinforcing existing ones and taking monopoly profits from them; monopoly is thus seen as a natural result of competition instead of its opposite. In particular, following Schumpeter, a large number of competitors is not considered as a necessary condition for competition; it can be found, usually to a greater extent, in oligopoly and even in monopoly (in a potential form). Finally, innovation (in a wide sense) is its driving force. The precise role it plays depends on specific characteristics of industries and markets and related competitive factors, but in no case should it be taken as a secondary issue. In this framework, a slow pace of innovative activity and/or of technical progress in a given sector or a given moment should be viewed as a particular case or a particular moment along an otherwise dynamic industry or product cycle, instead of a completely autonomous situation requiring static analytical tools. In other words, a situation where competitive forces are dampened or relatively well balanced can only be explained in a dynamic framework; but the reverse is not true.

Technological paradigms and trajectories are the basic evolutionary analytical tools in this respect (Dosi, 1984), since they are designed to explain the main sources of long-run regularities as well as long-run changes. As is well known, the first concept is borrowed from T. Kuhn's scientific paradigms, sharing its cyclical, non-linear direction of knowledge evolution in specific areas (scientific or technological), as well as its emphasis on the importance of the diffusion and reproduction, within the relevant community, of common references, procedures and approaches that direct research efforts.

Technological trajectories, on the other hand, are seen as a time sequence of progressive shifts of trade-offs between techno-economic variables, specific to a given technology, which indicate technological progress and which stem from innovative efforts of firms and institutions (including public ones). A paradigm may involve many trajectories (corresponding to different products and processes) through which it evolves and reproduces itself, and to whose progressive exhaustion it owes its being transformed and eventually surpassed by another. During transitions between technological paradigms they may coexist with one another, especially when the old one's sunk costs, and/or the new one's uncertainties and investment requirements, are high enough.

From this theoretical standpoint, sector specific, firm specific and even institution specific features should receive great emphasis, even more than generic ones, since innovative efforts, by definition, lay heavily on the search of technological diversity as well as market opportunities with a view to differential profits. In this sense, the analysis of competitive forces at work within a given industry and corresponding market(s) should focus mainly on factors that generate structural competitive advantages and asymmetries such as technological opportunities, cumulativeness (learning process) and appropriability (profitability) that characterize its technological trajectory and market opportunities (Dosi, 1984).

Sectoral taxonomies based on specific factors that explain differences in the generation and diffusion of innovations, such as in Pavitt (1984), are then a good starting point to an account of sector specific features of the dynamics of competition within any industry. Under Pavitt's classification, agriculture should clearly be considered as a 'supplier dominated' sector.

Like many industrial sectors under this heading, most of its markets exhibit a very low degree of market concentration and absence of oligopolistic structure; product homogeneity and a high level of price competition; low rates of technical change and a very limited capacity of innovating by its own means, with insignificant R&D expenditures. Innovations and technical change in agriculture are almost entirely due to supplier industries, both equipment manufacturers and input suppliers (fertilizers, seeds, pesticides). In addition, the remarkable presence of public policies and of public institutions providing research funds and carrying out research activities cannot be overlooked.

All of this could be taken to suggest that an approach focusing on innovation and competition would be misplaced here. However, as mentioned before, sector specific characteristics are not only acknowledged in this approach; they constitute its very basis. Agriculture (and its specialists, economists or whoever else) should not claim to be so different from other (industrial) economic activity sectors as to justify a whole economic analysis, or even a theory, for its own use. At least nothing more special than, say, textile, clothing, footwear or even food industries – so different from one another in so many respects.

But this is not to say that to analyse this sector as a 'supplier dominated' one is enough. Even to treat agriculture as a 'sector' is not enough. Last but not least, technological trajectories and sources of innovation are also not unique in agriculture, its diversity being a very important issue to understand its competitive dynamics from our theoretical standpoint.

Before getting into more detail about these sources of specificities, let us state briefly which are, in our view and under the present approach, the basic *common* elements needed for an economic analysis of activities related to agriculture:

1. the nature of technological paradigms (and corresponding trajectories) that are effective, their trends and evolution and eventual processes of technological convergence they entail;
2. strategic and behavioural responses of agricultural units (firms or producers) to market signals and opportunities as well as technical change perspectives defined by the technological trajectories in course;
3. selection processes, through markets or other institutions, involving either new competitive patterns and competitive strategies coming from downstream industries (agro-industries) or new technological opportunities.

All these aspects provide not only a common frame of reference shared with other sectors under the same approach, as well as to agriculture markets, sub-sectors and related industries; they also help to frame the analysis of specificities in agriculture in a less arbitrary way than is normally found in the literature. For instance, the existence of technological trajectories and even a convergence between some of them may be a decisive factor to understand the chief long-run trends of this sector (Item 1); the scarcity of big business units in agriculture should not imply that they are nothing but price takers with no strategy whatsoever and that no time should be spent in the study of their market and technological behaviour (Item 2); and the impressive presence of the state and research institutions in this sector's selection environment should not lead to the false presumption that deterministic non-market trends (either technological and/or institutional) definitely prevail over market concerns (Item 3).

What are, then, the basic characteristics of agriculture that under the framework above, exhibit major specific features for an economic dynamic analysis? In brief:

1. Technical basis of production depends strongly on natural conditions, which affect its technological trends. Both space and time dimensions are involved here. The former concerns natural advantages that benefit firms or producers well located as to specific cultivation under a given technology, transportation routes and distance from con-

sumption centres (as also found elsewhere in industry). Innovations can compensate for such natural differences, but cannot eliminate them since these advantages can also be enhanced by technical improvements. The time dimension is related to biological cycles that prevail in agriculture and, within some limits, are responsible for an 'unusually' long production period, common to all producers in the same market. Technological trajectories and market behaviour are also affected by such features. [1]

2. Sources of cost reduction associated with business size and range (the economics of search and scope so often found in industrial activities) are very limited in agriculture. With few exceptions, they usually are relevant only at small cultivation and market sizes. As a result, it lacks the most important conditions that generate and consolidate large productive units, big business and high market concentration that are so widespread, although obviously not absolute, in industrial sectors.
3. Size and organizational characteristics of producing units and firms vary widely, but there are strong conditions (in part due to the above reasons (2)) limiting their growth and diversification range. Larger units are often associated with upwards vertical integration from agro-industries, due to high transaction costs with crowded supplier markets. The usual identification between contemporary capitalist development and large-scale enterprise contributes to a large extent to support the wrong view of a productive sector based mostly on small-scale family business units, as being backward or even 'pre-capitalist'.
4. Its degree of technological appropriability is very low (as is the case, by the way, with other 'supplier dominated' sectors) implying a considerable lack of attractiveness of R&D and other innovation efforts specifically by agricultural firms, as already noticed, suggesting also an image of technological backwardness and low productivity gains. Together with the virtual absence of oligopoly, or the low concentration of its markets, it easily attracts the misleading label of perfect competition. However, as again can be found in other sectors, competitive as they may be, agricultural markets are also permanently subject to technology improvements, upstream innovations and even learning processes through interaction with suppliers (such as equipment manufacturers) which create competitive (cost, price, productivity, quality) advantages over competitors and competitive 'disequilibria', just as in other markets. Although under similar technological trajectories and competitive conditions and sharing the same 'supplier dominated' subordinate position, producers many differ not only in risk aversion, but in many other relevant ways – income, size, financial conditions, productivity, learning capacity, technical competence, information, etc. According to these dynamic characteristics of ruling technological paradigms and corresponding trajectories, as to the timing, scope and importance of technological opportunities, cumulativeness and appropriability they entail, different expectations, decisions and virtuous performance effects may emerge at the firm level. Competitive asymmetries will thus arise in the market as a permanent, not a transient feature; even in this case, perfect competition will be a blurred picture and a misleading model.

[1] Even the land tenure regime can be considered as part of the competitive process in agriculture production.

3. Sources of innovation and technological trajectories in agriculture

A dynamic approach to the process of innovation in agriculture requires the variety of agents contributing to conform the 'technological regime' in force almost everywhere in the last 30 years to be taken into account. Sources of innovation in agriculture have diverse disciplinary as well as competitive strategic origins. What we call the technological regime of modern agriculture involves not only industries, such as chemical, pesticides, pharmaceutical, seeds, machinery, tractors and mechanical tools, food, etc., but also public research and education institutions, producer organizations as well as private and public research foundations.

To be classified as 'innovation taker' does not turn agriculture into a homogeneous entity, with unique innovative dynamics. It comprises a set of technological trajectories of different origins, conformed by different economic and disciplinary environments. However, the shaping of a technological regime and its corresponding trajectories influence each other, thus creating a degree of coherence that some authors interpreted as a deliberate movement organized by capitalist agents towards the diffusion worldwide of a 'technological package'. [2] Surely, the very notion of technological trajectory precludes such determinism and even points to a multi-determined interpretation of the process of innovation, in agriculture or elsewhere.

To study technological trajectories in agriculture involves, therefore, the admission, basically, that:

1. there is no such thing as a general technological trajectory in agriculture, where one homogeneous technological and competitive situation could be found;
2. the concept of technological trajectory cannot be taken as a wide sectoral concept, but as linked to specific competitive dynamic trends of markets (agricultural or others) which express the most likely paths to be followed by the asymmetry creative pressures from the competitive process through innovation search and selection mechanisms (Nelson and Winter, 1977, Nelson and Winter, 1982);
3. the trajectories of industries related to agriculture should be considered, in their interrelations with agricultural markets.

In the following we propose, as a first step to identify technological trajectories prevailing in agricultural production since World War II, a taxonomy of its sources of innovation. We consider that the institutions which provide or support innovations to agriculture can be classified into six main groups, defined in terms of their behaviour in generating and diffusing innovations.

1. *Private sources of business industrial organization*, whose main business is to produce and sell intermediate products and machines to agricultural markets. They comprise, as concerns plant agriculture: (a) pesticides industry, partly related to pharmaceutical and chemical industries; (b) fertilizers industry; (c) machinery and equipment used in agriculture, divided into tractors and farming tools on the one hand and other equipment on the other (e.g. irrigation); (d) seeds industry comprising hybrids (specially corn and sorghum), vegetables and varieties of large cultivation. As to animal husbandry, besides some coincidences with the above list, one can also add the following industries: veterinary products (part of which is linked to pharmaceutical); animal foodstuff; genetic matrices; equipment to farm constructions.
2. *Public institutional sources*, comprising universities, research institutions and public research enterprises. They run basic research activities on plants and animals; technology development and transfer; product development and tests to supplier industries of the first group. The basic concerns of this group are: (a) to extend scientific knowledge in plant and animal sciences and other related scientific fields; (b) plant and animal improvements and development of new cultures and races; (c) to establish and prescribe more efficient agricultural practices.
3. *Private sources related to agro-industries*. They comprise agricultural product processing industries that interfere directly or indirectly in raw material production. The diffusion of the technology it produces benefits industrial processing stages. For example, forestry firms making their own plant genetic improvement; pork and food meat processing firms develop methods of organization of agricultural production that they pass on to integrated producers (to whom they are also in part responsible for the prescription of technical production standards). The action of these sources may be either individual, coming from industrial processing firms which establish standards for the producers, or collective, through the formation of consortia to develop generic technologies that could be 'homogeneously' appropriated in a precompetitive phase. For example, large pulp and paper firms act in both ways, making in-house research and R&D partnership.
4. *Private sources, collectively organized and nonprofit oriented*, include producer cooperatives and associations whose main purpose is to develop and transfer new seed varieties and agricultural

[2] This interpretation can be found in the extensive literature produced in the 70s and 80s about the Green Revolution. See, for example, Griffin (1982).

practices such as new planting methods, fertilizer and pesticide dosage, methods for pest control, animal breeding, irrigation, crop storage, etc. Besides direct transfer, technology in these cases can also be sold, although such sales do not usually follow the same pricing criteria as in the first group, since such organizations are not exclusively dependent on product sales. Even if they are not strictly profit seeking business organizations, they can strongly influence competitive patterns in some markets, from traditional ones, like seeds, to new products, like biological nitrogen fixing micro-organisms, thus adding their strategic choices to competitive environments they act on.

5. *Private sources related to services supply*, such as firms selling technical support services, planning and production management and services related to grain production, crop and storage and animal breeding. Two basic types are found: (a) firms selling assistance to agriculture planning; (b) firms selling specialized technical services, such as soil systematization (Fanfani and Lanini, 1992), embryo transfer, insemination, etc. Although in some cases firms may generate innovations, this group is mostly made up of technology disseminators. Their competitive advantages are usually based on the development of specific skills and on the amount and quality of information the firm is able to process.
6. *Farm production units*, through which new knowledge is established in the learning process which sometimes can be translated into innovations, although not embodied in new products. Despite their historical loss of importance in genetic improvements, farmers are in many cases directly responsible for the raising of new varieties. Of course there are skills and tacit/specific knowledge developed by farmers, as a result of their farming practice, in a typical 'learning by doing' process. The larger this amount of knowledge, the greater may be expected to be the degree of cumulativeness and the degree of technological capability, allowing him to get competitive advantages.

The way in which these sources evolve and relate with each other is the main institutional driving force that develops the technological trajectories in agriculture and gives a comprehensive and coherent pattern to modern technological regime in agriculture.

In sum, technological regime in agriculture involves great complexity. It is difficult to quantify precisely the importance to be ascribed to each one of the above groups. However, there is an appreciable predominance of the first and second groups. The so-called 'upstream industries' and public research centres have certainly been the two poles from which the current technological regime in agriculture was developed.

Regarding the innovative dynamics, it is worth noticing that within agriculture-related industries one can find all types described in Pavitt's taxonomy. There are typical 'science based' industries, such as pesticides (Achilladelis et al., 1986) and seeds (Joly and Ducos, 1993); there is a 'scale intensive' branch, as chemical fertilizers; one 'specialized supplier' such as farm machinery (Sahal, 1981; Fonseca, 1990) and finally a 'supplier dominated' (Fanfani et al., 1992), as food industry. If we include the 'information intensive' type as in the latest taxonomy version (Bell and Pavitt, 1993), a services group could also be classified.

It should also be added that the technological trajectories shaped inside each of these groups involve not only distinct dynamics of innovation but were originated in different historical situations and with different purposes, not always related to agriculture. While the tractors and tools industry dates from the beginning of the last century, pesticides would only set up in early 20th century; and while the former was initially developed to farming operations, pesticides derived from products developed for other aims (as dyestuffs, rubber additives, among other applications).

The technological coherence that can now be found between different usual technical procedures in agriculture has been built for the last one and a half centuries and represents the intersection of technological trajectories that evolved under particular technical and economic conditions which were convergent in some respects. This coherence is an *evolutionary* result of different trajectories which led to the consolidation, in the second half of this century, of a general technological regime (following the definition by Nelson and Winter, 1982), characterized by the intensification of output per area and per worker.

This notion involves the assumption that regularities do exist, as a consequence of technological opportunities, learning processes and selection mechanisms, in spite of the presence of strong uncertainty elements as an aggregate result of decision processes. The existence of important complementarities among technologies entails more or less organized forms of coordination.

Technology in agriculture is, by definition, multidisciplinary, since it involves at the same time the management of physical conditions, as some soil properties and changes in temperature, insolation and moisture; chemical ones, as the availability of essential elements in specific molecular forms; biological ones, which are more complex in so far as they concern not only the functioning of individual organisms (plants, animals and micro-organisms) but also the effects of their interactions with one another and with the environment.

The complexity of soil–climate–living organism relations is such that the use (and sometimes the development) of a particular technique or an input involves the use (or development) of at least another directly related. This can be found, for example, (a) between harvesters and dwarf varieties whose architecture is more fitted to the machine work, as well as with varieties more resistant to physical damage; (b) between high yield varieties and the intensive use of specific fertilizer formulae and of large volumes of water (as wheat and rice varieties in the Green Revolution); (c) between fertilizers and pesticides and machines designed for their application; (d) between the use of pesticides and the related increase in use of high yield varieties which usually exhibit an inverse relationship between productivity and resistance to pests and diseases. [3]

As pointed by Dosi and Orsenigo (1988, p. 32), there is order in change, created by a varied combination of learning patterns, selection mechanisms and institutional structures. "The dynamic coherence (homeorhesis) of economic systems in conditions of technical change, we conjecture, is the outcome of particular 'architectures' or forms of 'regulation' which define the functioning and the scope of markets in relation to the specific properties of technological paradigms, the prevailing forms of behavior and expectation formation of agents, the structure of the interdependencies of the system, and, finally, to the nature and interests of the institutions which play an active role in the economy."

Therefore, technological convergence can neither be taken as a fully coordinated, ex ante defined process, nor as a chance event. Two basic coordinating instances can be identified: (a) firms which generate technology by embodying technological elements in their search strategies, as in the examples above; (b) education and research agronomic public or private institutions, through their coordinating and gathering action.

Besides these formal instances, a third, not necessarily formal, can be added: qualitative flows developed between technology users and producers represent one more institutional *locus* leading to organized efforts, which promote the interaction of different technological dimensions necessary to agricultural production. The presence in the field of a technology producer close to R&D formal organizations and to the farmer, facing such technological complexity, creates a cognitive structure which can lead to a convergence of general guidelines as far apart as those between a larger pesticide firm and a machine manufacturer, or between these and a big seed producer, and so on. These are parameters and basic guidelines, of an integrating nature, that have developed and are now incorporated in the innovative routines of such firms (Salles Filho, 1993).

We then conclude that no a priori matching exists between technologies arising from different sources, as if agents worked purposefully to produce a homogeneous whole. What does happen is an iterative process, through which general technical and scientific concepts spread among innovation agents are assimilated in search routines. This amounts to an essential feature of the concept of technological regime.

We thus suggest that the interpretation of technological trajectories and of the formation of a technological regime in agriculture should be made on the

[3] One can also find several complementarities in agricultural products processing.

basis of the notion of 'problem areas'. [4] It is possible to figure such 'areas' as more or less evident general problems in agricultural production (as, by the way, in other activities). The nature of such problems is essentially technical and the corresponding solutions are conditioned, or even directed, by the ruling technological regime. The reverse is also true: a given technological regime may be affected by the particular forms these solutions take. A succession of such solutions characterizes a given technological trajectory, as defined above. Our claim is that the emergence of such 'problem areas' in production and respective solutions have guided the course of technological trajectories, given the already mentioned technological regime consisting of production intensification and corresponding productivity gains.

In search of production intensification, several techniques to control living organisms and environmental conditions were developed. Pest and disease control methods, increasing of the grain/straw ratio, the control of soil conditions, water and nutrients supply, etc., were 'problem areas' for which several solutions have been proposed. Some examples of prevailing solutions are: chemical pesticides, the Mendelian method applied to genetic breeding to improve plant and animal productivity, the employment of high powered agriculture machines and the large use of chemical fertilizers.

The technical superiority of chemical fertilizers as compared with, say, organic ones, and of chemical pesticides vis à vis other control techniques, were clear. Plant response to large doses of superphosphate and ammonium sulphate (or ammonium nitrate and ammonia) was clearly superior to the results obtained by the use of Chilean nitrate, bone meal and guano. In the same way, the effects of chemical pesticides against insects and fungi were immediate and incontestable. The environmental problems due to these inputs could not be considered, at that time, 'problem areas', as they are nowadays. The discovery in the 50s and 60s of insect resistance and environmental persistence of certain pesticides and the water pollution effects of nitrates, were not sufficient to change the course of the existing technological trajectories.

Other technological trajectories could certainly be developed, but it is useless to discuss what could have happened instead. However, from a historical perspective, it is helpful to consider the scientific, technical, economic and social elements that produced the trade-offs among several possible trajectories.

Since the main objective of this article is to interpret the innovation process in agriculture on a dynamic basis, we suggest that in periods of fast change the analysis of technical change should consider: (a) indications of weaknesses in the present technological paradigms; (b) the arising new technological opportunities; (c) the influence of the existing barriers; (d) the relative importance of each 'problem area' in agriculture production (whether they are more or less critical); [5] (e) the arising new 'problem areas' (e.g. the ecological pressure); (f) the relative importance of the strategies of the economic agents directly and indirectly involved in the innovation process.

This approach has the following advantages: firstly, it identifies the different innovative strategies, as opposed to the usual interpretations in rural economics literature. Whatever the theoretical framework, most interpretations take the disciplinary origin of technologies as an explanation. In other words, the traditional classification of chemical, biological and mechanical innovations are ordinarily employed to explain the dynamics of technical innovation in agriculture. [6] Secondly, it avoids simplistic historical interpretations like those considering technologies as 'natural' solutions. Finally, it allows a dynamic interpretation of the innovation process through an

[4] This notion is inspired by Rosenberg's 'focusing devices' (Rosenberg, 1969, Rosenberg, 1982).

[5] See Bonny and Daucé (1989), OTA (1992), Brown and Goldin (1992) and Petit and Barghouti (1992).

[6] Even in the Neoclassical approach of induced innovation (Hayami and Ruttan, 1988) and in some Marxist analysis (Mann and Dickinson, 1978), this classification is used in order to explain the 'logical' movement of innovations in agriculture. In the first case, chemical innovation (as fertilizers) came to save the factor 'land' and the mechanics, obviously, came to save 'labour'. In the second case biological innovations are developed to reduce 'dead time' in the production process (the production phases in which there is no direct labour being applied).

evolutionary approach, in which problems and solutions become variables instead of parameters.

4. Towards a new technological regime in agriculture

In this section we present the main changes that are currently transforming the agricultural technological basis. We briefly discuss the process of exhaustion of the present technological regime and the main trends that may be envisaged.

Present changes in agriculture production are increasingly visible and they have arisen from several causes. From deep changes in policies towards agriculture (such as cutting down subsidies and reducing food security policies) to pressures from ecologists (for a sustainable agriculture), there are many factors that undoubtedly point to major changes. Additionally, this is a global and integral process. It is global because it is not a regional or a local phenomenon, and it is integral because it encompasses all components of the technological regime.

What all this amounts to, is a strong internally coherent pattern, with a particularly difficult ranking of the different sources of change. From merely didactic perspective, with no aim at a full classification, we suggest that the transformation in progress can be analysed in two complementary ways. The first one, which we called *internal*, is related to the dynamics of innovation sources; the second one, called *external*, concerns the economic, scientific

Table 1
A perspective of technological change in agriculture in the short and medium term (after Bonny and Daucé, 1989)

General characteristics	Changes in progress and expected	
	Next 10 years	More than 10 years
Scientific basis	Cellular biology and 'routinization' of molecular biology 'Routinization' of microelectronics	Molecular biology Molecular engineering Microelectronics
Technological basis	Still conventional breeding techniques, chemistry, mechanics, but: The introduction of information technologies and microelectronics Employment of new techniques based on cellular biology (such as tissue culture) Development and 'routinization' of DNAr techniques Employment of mechatronics	Broad diffusion of the new techniques
Objectives of technology development	Productivity considering qualitative aspects Indirect gains in productivity Beginning of product diversification Ecologically concerned techniques (LISA – low input sustainable agriculture)	Innovation in products as important as in process Qualitative tasks as new guideposts New environmental harmless inputs
Sources of innovation	The same, with increasing participation of agriculture industries and redefined relations between public and private research	Essentially the same with possible participation of new biotechnological firms, and firms providing mechanization, informatization and animal reproduction services Public institutions more market-oriented and with biodiversity concerns

and social environment.[7] In the first case it is worth enforcing: (a) the study of the conditions of technological opportunity, appropriability and cumulativeness (Dosi, 1984) associated with the existing technological trajectories; (b) the analysis of search strategies and institutional organization in each innovation source. In the second case (the external pressures) one has to analyse global movements in social, institutional, economic and scientific levels, which have or may have significant influence on the new technological trajectories. In this sense, we propose the following fields of analysis:

1. The organizational and strategic changes related to the sources of innovation, as listed below:
   1.1. the industries of pesticides, fertilizers, seeds and machinery and equipment;
   1.2. the industries of agriculture;
   1.3. the specialized services firms;
   1.4. the public research institutions;
   1.5. the R&D arrangements of farmer organizations.
2. The external changes with direct and indirect impact on the technological trajectories, comprising the following instances:
   2.1. changes in agricultural policies, especially regarding the support of farmers rent (with decreases in the subsidies level), the international trade (reducing trade barriers) and the food-security programmes (decrease of importance in US and in EC caused by the achievement of high production levels);
   2.2. pressures from environmental/ecological sources;
   2.3. advances in the field of molecular biology and the related biotechnology techniques;
   2.4. new food consumption patterns, especially regarding nutritional and health concerns.

Of course these instances cannot be detailed in this article. They make up a research agenda. However, we intend to give a brief account of the general trends likely to occur in the short and mid term. Table 1 (based on Bonny and Daucé, 1989) presents a summary of the main changes in progress and the expected results in the near future.

The basic analytical content of this table is the exhaustion of the technological regime based on productivity gains. The search for increasing yields per area (or per labour unit) still is an objective, but it loses significance as compared with other goals, especially those related to quality. This new direction implies the beginning of a new phase of product innovation in agriculture.

Presently, agriculture exhibits new 'problem areas' as a result of the simultaneous occurrence of the above factors. The precise direction of technological trajectories is obviously unknown. But it is important to find out precisely how the new 'problem areas' are being incorporated in the innovative strategies and how the role of each source of innovation, including the possible emergence of new actors, is being changed.

Taking the example of the environmental problem area, its solution involves almost all the whole technological pattern. Besides the pollution effects of fertilizer production itself, its large-scale use has caused water contamination and increasing soil salinity. Such a situation has entailed some alternatives: (a) better agronomic practices in order to rationalize the use of fertilizers strictly matching the recommendation with soil and plant needs; (b) development of varieties with low fertilizer requirements; (c) development of new formulae to diminish fertilizer losses when applied to some kinds of soils (acid soils, for instance, which retain more than 80% of the phosphate).

In the pesticides case, the pressures for environmental and health risk reduction have led to such changes as: (a) development of products with faster degradation in the environment; (b) development of pest and disease resistant varieties, with particular emphasis on transgenic plants; (c) increasing importance of biological control and integrated pest management.

As can be seen, there are several possible paths and each one results in completely different technological trajectories. The fertilizers industry, a typical scale intensive industry, has been facing a narrowing of technological opportunities. The exploitation of scales and labour division, the improvement in organizational methods, and the search for incremental

[7] In a broad analogy, these can be understood as the factors influencing the process of search (internal) and selection (external).

innovations, have been insufficient to ensure competitiveness at the international level. The future of the fertilizer industry depends on external and internal (regarding the competitive process) determinants. However, since a new paradigm is not yet defined, the technological trajectory which will prevail in the plant nutrition 'problem area' is unknown, both an 'optimization' and 'radical' alternatives being possible. The 'optimization' solution which involves rationalizing the use of chemical fertilizers, so as to reduce their consumption, seems to be, in the short term, the most feasible option. Nevertheless, it will certainly be contested in the long term, because it is a demand-depressing alternative and will reinforce competition. A 'radical' option could be a strong development of transgenic fertilizer-independent varieties, which would lead to a completely new trajectory, with new economic actors in the innovation process.

Also in the pesticides industry, although in a different way, an exhaustion of technological opportunities has been taking place. The cost of developing a new molecule has soared impressively in the last 15 years, reaching on average more than $130 million per molecule. This situation became even worse due to the regulatory process regarding pesticides production, transportation and use. Among alternatives likely to be undertaken, three deserve attention: biological control; new resistant varieties; new methods for chemical synthesis. These options are of course not exclusive, but they imply impressive changes in present trajectories. The alternative of a large diffusion of biological control means the enlargement, on a global scale, of an industry producing micro-organisms, insects, biological toxins, etc. To the same extent, the development of transgenic varieties incorporating genes that increase resistance to pest and disease will mean a deep reorganization in pesticides and seeds industries. [8] In the third alternative, it is possible that new technologies will replace the traditional screening method by using deterministic techniques based on molecular engineering and on molecular biology. It will entail a new chemical technological trajectory, because it assumes that chemical synthesis will be able to produce the designed molecules.

At the present stage of development it is very difficult to state which technological alternative(s) will prevail. In both examples (fertilizers and pesticides) it is possible that the same actors become leaders in the new trajectories, as much as new actors can arise. The opportunities opened by modern biotechnology may strengthen existing trajectories (at least in the short term) as much as they may entail new ones. The development of herbicide-tolerant varieties using transgenic methods is a well-known example. It employs the new knowledge to reinforce old markets. To sum up, we believe that in the short term a transition stage is likely to occur in agriculture, as we suggested in Table 1 above.

In any case, to define a new technological regime in agriculture is difficult, not only because it involves speculating about the future of technologies, which is uncertain by definition, but because we are witnessing a shift between paradigms, where the old one is not completely exhausted and the new one is far from being well defined. The basis on which the development of technological trends in agriculture were forecast does not seem to be appropriate any more. On the other hand, the swiftness with which new technologies (e.g. biotechnology) are evolving settles a high degree of uncertainty and turns prospecting into a hard and dangerous task.

5. Some conclusions

The main purpose of this paper was to suggest a new approach to the analysis of the dynamics of agriculture based on the evolutionary theoretical framework. This implies the emphasis on the nature, sources and consequences of innovation and technical change not only to production and productivity, but also to patterns of competition, interindustry dynamics and market changes. It also implies a sectoral focus, from which many heterogeneous features of agricultural technology production and markets, often left at a minor position, can be highlighted and take an outstanding place in the analysis.

Under this approach it was possible to suggest that, in spite of some particular characteristics of

[8] In fact this reorganization is already in course. Since the 80s the established pesticide firms (which in many cases are also chemical and pharmaceutical companies) took over several seed firms.

technology, production and markets that are common to different activities in agriculture (such as a low degree of appropriability from innovations, a strong dependence on natural – biological, physical, chemical – conditions and a low degree of market concentration) they cannot be taken as sufficient to prevent analysis from focusing main sectoral features under an evolutionary approach, as technological trajectories, sources of innovation and of competitive asymmetries, like any industrial sector; let alone to treat agriculture as an autonomous and relatively homogeneous whole, as in most of the literature.

Not only different links from agriculture to industries were considered – both 'downstream' (agro-industries corresponding to different products or product lines, mainly food industries) and 'upstream' (fertilizers, pesticides, seeds, farm machinery), as their characteristics and trends. The existence of significantly different sources of new technology and innovation were pointed out (private industrial R&D, public institution's R&D, private cooperative R&D, specialized service suppliers' R&D and even farm unit learning). As a result of such complexity, different technological trajectories can be envisaged, based on different historical purposes and industry initiatives. However, some significant elements of technological coherence can also be found, as an evolutionary result of common elements embodied in different intertwining guidelines and 'problem areas' in such trajectories, to the point that it seems possible to identify something like a technological regime in agriculture.

Present changes in course in agricultural technologies were also considered and an eventual trend to a new technological regime was discussed, together with the assumption of the coming exhaustion of the present regime. Sharp changes in research costs, public policies (subsidies, funds), the arising of new 'problem areas' such as ecological pressures and the perspectives for new developments in the technological basis (DNA-r techniques, new cellular biology techniques, mechatronics) are taken into account for that possible trend. However, more important than getting to a (possibly premature) conclusion is to open up a new research agenda, trying to provide answers to such questions as: which technological trajectory is likely to prevail in each industry segment; in which cases will old trajectories probably coexist for some time with the new one; for how long will a transition phase from the present technological regime to the new one run, and what will be the main characteristics of the latter, including its consequences on products, markets and competition, for the mid-term future? We hope we have been able here to suggest some items on such an agenda and, what is probably more important, to have stressed its relevance.

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