Research Policy 32 (2003) 573–586

research policy

www.elsevier.com/locate/econbase

Research and technology policies in innovation systems: zero tillage in Brazil

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Received 29 May 2001; received in revised form 17 July 2001; accepted 21 March 2002

Abstract

The increasing complexity of technology development and adoption is rapidly changing the effectiveness of scientific and technological policies. Complex technologies are developed and disseminated by networks of agents. The impact of these networks depends on the assets they command, their learning routines, the socio-economic environment in which they operate and their history. In this new environment, scientific and technology policies should: (1) foster interactions among agents (whether public or private), (2) increase the effectiveness of public research, extension and funding institutions, (3) give sufficient freedom to researchers to set their research programs, and (4) monitor the quality of research (rather of research outputs). The evolution of innovation networks is analyzed looking at the development and diffusion of zero tillage (ZT) in Brazil.

Keywords: Participatory research; Innovation networks; Complexity; Complex technologies

1. Introduction

Public research institutions and research policies in many developing countries have recently gone through major transformations. The changes sought to increase research impacts through the introduction of more formal planning methods, management by objectives and new funding procedures, especially competitive grants and sales of goods and services (Byerlee and Alex, 1998). These changes, however, often resulted in weakened research systems because the new procedures better suit repetitive tasks than highly uncertain and changing research processes.

Research processes are best understood in the framework of complexity theories.[1] In particular, it has been shown that the greater the complexity and novelty of the technologies being developed, the more difficult it is to control their development and diffusion. Traditional strategy and control mechanisms are of little use in the development of these technologies because chance and self-organization play a greater role in them than in more mature or simpler technologies (Lane and Maxfield, 1997). These lessons, though, have seldom been used in developing countries for the analysis of the interactions between the organization of research systems and the performance of the innovation system or for the design of research policies.

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[1] There are many definitions of complexity. In this paper, I define a complex system as the one where there are many interactions between many different components (Rind, 1999).

PII: S0048-7333(02)00058-6

This paper looks at the role of public research institutions and research policies in the emergence and evolution of innovation networks producing complex technologies through the study of the development of zero tillage (ZT) in Brazil. The main conclusion is that, instead of seeking control and efficiency, research policies should: (a) emphasize monitoring the quality of research programs, (b) foster risk-taking by researchers and research administrators, and (c) encourage interactions among agents in the innovation system. In addition, technology diffusion programs should not select a priori particular technologies but foster the simultaneous trial of several alternatives allowing farmers to chose those that best fit their needs.

ZT is the most important agricultural technology adopted in Brazil in the last 50 years. It reversed soil degradation, enabled the expansion of agriculture into marginal areas, boosted farmers' profitability and increased the sustainability of agriculture. While in the early 1970s, the area under ZT was negligible, by 2000 it was used on nearly 14 million ha.

ZT is a complex technology that requires the integration of many components: seeds, agrochemicals, machinery, agricultural practices (including crop rotations that span over several production cycles) and knowledge, all interacting with nature. ZT is very sensitive to ecological conditions and, thus, requires substantial adaptation to local conditions. Since many factors (natural and man-made) interact differently under ZT, the reasons why ZT is superior to conventional tillage (CT) are only partially understood, even by scientists.

ZT is not only a production technology, it is also a social construct. Although ZT research and extension programs have been implemented in more than 40 countries, massive adoption only occurred in the few regions were networks that used participatory research and extension methods emerged[2] (Ekboir, 2002).

ZT networks involve many agents (input suppliers, farmers and researchers) interacting through formal and informal links. The Brazilian network was no exception; it emerged as a result of the pressing needs of commercial farmers for sustainable technologies, the commercial interests of input suppliers and weak public research and extension systems. Many of the interactions were planned while others happened by chance, i.e. the evolution of the ZT network was a random process where several technological alternatives were tried and discarded. These alternatives were developed independently by different groups of agents. But the public research and extension institutions were, with only two exceptions, detached from the ZT process until it had been massively adopted by farmers.

Innovation is a broad concept that includes tangible and intangible outputs as well as small organizational changes. Thus, no representative measures of innovation have been found. Research and development indicators measure only formal research but do not include resources invested, for example, by farmers in trials in their fields. In the case of ZT, all quantitative information is lacking. To analyze the innovation system that generated ZT in Brazil, I interviewed 62 key informers in Argentina, Brazil, Paraguay, the US and the UK—including early developers and adopters, researchers, and input suppliers—and reviewed relevant literature.

As most complex technologies, ZT can be analyzed from different perspectives. Section 2 describes its agricultural features, the economic characteristics relevant to its development and adoption are reviewed in Section 3, issues related to research on ZT are explained in Section 4 and ZT innovation networks are discussed in Section 5. The history of ZT in Brazil is presented in Section 6 while the current structure and performance of the ZT network, emphasizing the role of formal research institutions, is analyzed in Section 7. Section 8 concludes with policy recommendations to improve the performance of the research systems and of networks that develop complex technologies.

2. What is zero tillage?

ZT is defined as planting crops in previously unprepared soil by opening a narrow slot or trench of the smallest width and depth needed to obtain proper coverage of the seed. At least 30% of the soil surface must remain covered with plants or their residues (Derpsch, 1998). Although the name refers to only one practice, ZT actually is a complete farm management

[2] In participatory research methods, trials are planned and conducted jointly by researchers, farmers and/or input suppliers in farmers' fields under production conditions and outcomes are evaluated jointly by these same agents.

system that includes specific practices for planting, plant residue management, weed and pest control, harvesting and crop rotations.

ZT is sustainable only if it follows three principles: minimizing soil disturbance, covering the soil with plants or plant residues, and rotating crops. Because in ZT, the soil is not disturbed and remains covered, soil temperature falls, moisture is better conserved and the biological activity is greatly enhanced. Crop rotations break the life cycles of pests and diseases and helps in weed control, reducing the use of agrochemicals.

Soil management practices and weed control are the key differences between CT and ZT. In the former, farmers prepare a seed bed before planting by making two to six passes with a plow (depending on soil conditions) plus a similar number of passes with a harrow. On the other hand, ZT requires only one pass to spray a herbicide for weed control. In CT, weeds are controlled mechanically and chemically; in ZT herbicides, and sometimes crop rotations, are used. For historical reasons, a single herbicide has always been a key component of ZT packages (see below).

The ZT packages used in South America are a combination of equipment (including special planters, sprayers and equipment for residue management), agrochemicals and adapted knowledge (in particular, management under local environmental conditions).[3] ZT technology is very sensitive to local conditions and requires substantial adaptation from one location to another. Even systems known to work in a given area must be adapted to the conditions of particular farms in that area. For example, the most advanced farmers in South America adapt their practices to individual plots (Ekboir and Parellada, 2000).

Agricultural benefits obtained with ZT are: (1) improved control of erosion when combined with residue management; (2) improved soils (organic matter content and structure); (3) reduced turnaround time between crops, allowing planting closer to the optimal dates; (4) increased flexibility in the timing of operations; (6) improved nutrient mobilization; (7) better conservation of soil moisture, reducing production risks and enabling production in drier areas; (8) easier weed and pest control (Sayre, 1998). Most benefits increase with the years of continuous ZT use.

[3] Packages developed in other countries are not as complete as those used in South America (Ekboir, 2002).

3. Economic issues in the analysis of ZT

ZT has many economic advantages over CT: (1) reduces costs; (2) requires less fixed specialized capital (fewer implements as well as less tractor power are needed); (3) lengthens the life of agricultural equipment; (4) reduces labor requirements and simplifies labor management; (5) conversely, larger areas can be planted with the same amount of machinery and labor; (6) sometimes yields increase; (7) in certain areas, three harvests per year become feasible; (8) production risks fall; (9) production in marginal areas becomes possible; (10) the reduction in labor requirements (measured in time and effort) enables small farmers to undertake other income generating activities (provided that they can access the markets); (11) the system's agricultural and economic sustainability increases.

Although variable costs may increase in the first year ZT is used, they fall with the time the soil is not disturbed (Table 1). In 1999, fixed costs for a 200 ha farm in the first year under ZT were 25% lower than with CT (US$ 156 and 207, respectively, Roque Tomasini, EMBRAPA-Wheat Center, personal communication, 2001).

Several of the technology's characteristics facilitate its adoption:

1. In the first two years under ZT, the farmer obtains immediate benefits from the new technology. The transition reaches a critical point in the third year, when most factors particular to each farm (especially the evolution of pest and weed populations) need to be addressed. Some farmers never succeed

Table 1
Cost difference between ZT and CT for the rotation soybeans–maize–wheat in 1999 (US$)

	CT	ZT in the first year	ZT after 10 years
Total cost	532.27	549.67	370.52
Difference between CT and ZT (%)	100	103	70

Source: Roque Tomasini, EMBRAPA-Wheat Center, personal communication, 2001.

in adapting the package to their particular conditions, and revert to CT.
2. Sunk costs associated with the adoption of ZT are small. The main components of ZT are a special planter and knowledge. Since the ZT planter can also be used for CT, the only sunk cost would be the conversion of a conventional planter; this cost, though, is small. The other specialized inputs are the investments in learning the technology. None of these costs is important compared with the production costs incurred every year by a commercial farmer.
3. Investment indivisibilities are small. Last generation ZT planters are expensive, but are similarly priced to conventional planters of comparable quality. Also, there is an active market for second hand equipment, and the technology for converting conventional planters into ZT planters is well known and relatively inexpensive. Although the converted planter may not be as effective as a brand new one, it can do a good job.
4. ZT can be adopted partially or in stages. Usually, farmers try ZT on a small area until they command the package.

The main restrictions to the adoption and maintenance of ZT are:

1. ZT requires a complete departure from conventional farming practices. This has been one of the main difficulties for farmers who have been told for years that a fine tilth obtained through repeated plowing was necessary. Many researchers and university professors had similar problems in changing their research and/or teaching approaches, in particular after they had invested many years in researching aspects of CT.
2. The change from CT to ZT involves learning the dynamics of a system out of equilibrium which usually takes a long time (more than 5 years) to reach a steady state.[4]
3. Social pressure may deter potential innovators. Because traditional practices indicate that a good farmer plants in a clean field, early adopters of ZT can be labeled ‘lazy or crazy’.
4. Weeds, pests, and diseases may increase, especially when adequate rotations are not used.
5. Short-term economic considerations may deter farmers from using adequate rotations, thereby reducing the system’s sustainability. For example, until the mid-1990s, the price difference between soybeans and maize was more than US$ 100/t. Many South American farmers planted wheat and soybeans continuously knowing that they might increase future agricultural problems because the short-term price difference compensated the expected long-term yield reductions.

4. Key features of research and extension related to ZT

Research on ZT has particular features that invalidate the traditional economic approach for the analysis of technical change and highlight the need for an alternative framework. The most important features are:

1. ZT is a complex technology that involves physical inputs and adapted knowledge. Since all components have to be integrated into a package, the latter has to be developed by teams that include several agents (researchers from various disciplines, farmers and input suppliers). Participation of public research institutions in ZT networks was hampered by the linear vision of science that prevailed in them, their strict organization along disciplines and, often, incentives based on publications in peer-reviewed journals. Writing papers for peer-reviewed journals is more difficult for researchers that conduct interdisciplinary research or technology development.
2. Formal scientific agricultural research is a long-term process, in which researchers repeat experiments with a statistical design over a number of years before they issue recommendations. While some of the knowledge generated in this way can be obtained faster by repeating the same experience simultaneously many times in farmers fields, other knowledge can only be obtained through formal researchers in well equipped and funded institutions.[5] The reluctance of researchers

[4] There is even the question of whether a steady state actually exists and if the system ever reaches it.

[5] The issue is under which circumstances inferences can be made from data obtained without an experimental design. Many sciences, e.g. economics and astronomy, have developed statistical tools with this purpose.

to accept non-experimental information hindered their involvement in ZT networks.

3. Many ZT developments, especially the initial developments, are not science-intensive, i.e. even a lay person can compare a field planted with CT with one planted with ZT. This allows farmers to generate their own knowledge, yet with limited interactions with formal research institutions. As the technology matures, though, issues that require formal research procedures (e.g. the dynamics of weed populations) become more important. If the research system does not provide answers, farmers develop their own solutions, sometimes reverting to an inferior technology: CT.
4. The system's dynamics are endogenous, implying that a sustained research effort is required to maintain and/or increase its sustainability. In most countries, ZT depends on one herbicide (glyphosate). After several years of monoculture, new pests and more aggressive weeds have been identified, and development of appropriate weed management is crucial for the system's sustainability. Other issues that require sustained research are: evolution of soil structure and soil compaction, impact of soil structure on crop yields, and evolution of soil flora and fauna. Most of this research is science-intensive, and consequently has to be done in research institutions. Given the weakness or indifference of domestic research institutions, farmers' associations have relied on individual researchers and foreign research institutions.
5. ZT was a new experience in agriculture. Research for commercial crops had been conducted for a long time, and public research institutions had accumulated a wealth of knowledge about them. Additionally, the channels for generation and transfer of information were well established, so that all agents involved in commercial grain production knew where to search for information. In the case of ZT, the knowledge and the diffusion channels had to be created.
6. It is usually assumed that private research on commercial inputs should be close to the social optimum because these are private goods. On the other hand, knowledge, being a public good, should be financed with public funds. The ZT experience shows that reality is more complex than these simple recipes.

5. ZT innovation networks

Complex technologies are developed by networks that co-evolve with the technologies they generate (Rycroft and Kash, 1999). ZT networks usually involve researchers from public and private institutions, farmers, equipment manufacturers, input suppliers, government agencies, non-governmental organizations (NGOs) and financial institutions.

Agents participate in the networks through formal and informal arrangements. Participation in the network adjusts often, reflecting changes in the agents' objectives and evolving technological challenges. In general, formal or indirect interactions (especially mediated by markets) are prevalent for mature technologies because each agent has an idea of the potential of the technology, technical standards, and the needs and the roles played by other agents in the market. On the other hand, informal or direct interactions are more important in the early stages of a technology because there is greater uncertainty about the market potential, technical standards, the assets commanded by other agents and network participation.

The performance of innovation networks depends on their core capabilities, internalized complementary assets and organizational learning routines (Rycroft and Kash, 1999). Core capabilities are those aspects of innovation in which a particular network excels. Internalized complementary assets are the resources that the network can use to innovate. Organizational learning is the process by which capabilities and assets are acquired or discarded. The performance of an innovation network also depends on its history, the complementary assets that the network needs to acquire, and the environment in which the network operates.

The initial core assets of the Brazilian ZT network included: (1) a minimum formal research capability (a few researchers from agrochemical firms and public institutions) with a culture that valued innovation and networking (especially participatory research approaches), and (2) an agent (an agrochemical company) with sufficient resources and geographic coverage willing to play a catalytic role in the emergence of the network. This last factor was crucial. Individual researchers and farmers experimented with ZT in many countries, but widespread adoption occurred only when an agent took the leading role (Ekboir, 2002).

The complementary assets included agents with strong personalities who could organize local networks, innovative agents (in particular, farmers and equipment manufacturers), linkages with international sources of information and an extension system organized by farmers' associations.

Five new learning routines were adopted by the network: participatory research methods, a multidisciplinary approach to research, acceptance of information generated without an experimental design, creation of a common language that enabled communication between agents with different backgrounds, and active gathering and open dissemination of information. These routines required new types of interactions among agents, basically replacing the hierarchical structure arising from the linear vision of science with a horizontal structure in which farmers, researchers and manufacturers were equal partners.[6]

6. History of ZT in Brazil

Modern development of ZT started after the British company ICI discovered the herbicide paraquat in 1955. For centuries, it had been assumed that tillage was necessary to improve water infiltration and to control weeds. Several studies published in the UK in the 1940s showed that tilling could be avoided if weeds were controlled by hand. Now that weeds could be controlled chemically, ICI funded research in the UK to find out if cultivation was still necessary. After the first promising results, ICI realized that creation of a market for paraquat required a completely new agricultural technological package. ICI invested heavily to create in-house research capabilities on agricultural systems by hiring agronomists and mechanical engineers; ICI also assessed paraquat's technical and economic potential in several countries. Following these studies, ICI established a research team in Australia in the late 1960s.

ICI's involvement in the USA was limited because it had licensed paraquat to Chevron Chemicals and could not develop a market for itself. In 1960, university researchers in VA, USA, used a combination of herbicides (including paraquat) to control weeds. The experiments were soon repeated in other states. The University of Kentucky created a strong research program on ZT, led by S. Phillips, which later had close interactions with Brazilian ZT networks. The first use of ZT in commercial production was reported in Kentucky in 1962 and the first commercial ZT planter was produced in 1966. Taking advantage of the fact that ZT enabled farmers to plant immediately after harvest, the double cropping of wheat and soybeans was introduced in 1966 (Ekboir and Parellada, 2000).

Starting in the 1960s and for the next three decades, the Brazilian government encouraged a progressive expansion of the agricultural frontier towards the southwest, center-west and north. Agricultural practices became more intense as soybeans, as a single crop or in rotation with wheat, replaced livestock and coffee production. These changes, combined with heavy rains and a hilly landscape, led to serious soil erosion. Public research and extension institutions advised farmers to switch to livestock production. Some farmers, seeking to avoid the economic losses caused by the abandonment of crop production, began testing reduced tillage.[7] Among them, Herbert Bartz managed to minimize soil disturbance.

In the late 1960s, the German international cooperation agency, GTZ (Deutsche Gesellschaft fur Technische Zusammenarbeitz), based Rolph Derpsch at IPEAME[8] (Londrina, Paraná) to work on a project to increase soybean yields. After the first experiences in 1970, Derpsch realized that the intensive cultivation led to severe erosion and began trying alternative farming methods. He had read some papers that described ZT, and by chance he found in the experimental station a German planter that could be modified to plant without disturbing the soil. Encouraged by the results obtained with ZT, Derpsch teamed up with Bartz to try it in his farm. Derspch had the flexibility to recognize that his original research goal was wrong and rapidly

[6] Interactions between researchers and extension agents were usually shaped by the linear vision of science, in which extension agents and farmers provided little input to research. Moreover, their interactions were hierarchical: the researcher, being the holder of knowledge, educated the extension agents. This type of relationship was then recreated in the interactions between the extension agents and the farmers.

[7] In reduced tillage, the soil is disturbed less than in CT but more than in ZT.

[8] IPEAME later became EMBRAPA's Soybean Center.

changed the focus of his efforts. Equally important was the fact that he had the freedom to redesign his project based on the incomplete information obtained from the first trials.

In 1972, ICI transferred its ZT research team from Australia to Brazil where it soon became the hub of the system that developed the first ZT package.[9] This team rapidly established strong relationships with different agents working on ZT: Derpsch, a few researchers—mainly from the Agronomic Institute of Paraná (IAPAR) and the Wheat Center of the Brazilian Agricultural Research Corporation (EMBRAPA-CNPT)—pioneer farmers and equipment manufacturers.

Aware that adequate planters were a key input of any ZT package, ICI invested substantial resources in their development: it transferred a mechanical engineer from Australia to Brazil, it contacted several manufacturers until a small shop (Semeato) agreed to collaborate,[10] it imported a planter and made it available to researchers, manufacturers and farmers. From these efforts, a strong collaboration between ICI, EMBRAPA-CNPT and Semeato emerged. In spite of the proximity of Derpsch and the ICI team, IPEAME researchers and management did not realize the importance of ZT until it was extensively used by farmers. On the other hand, the director of EMBRAPA-CNPT was an innovative researcher and early in the process encouraged researchers to participate in the development of ZT.

In 1972, ICI helped Bartz and a neighbor to travel to the USA and UK to observe the latest advances in ZT technology. Both farmers imported ZT planters. When they used the technology on their farms, they encountered many problems, particularly with weed control and the planter's inadequate design. The neighbor eventually reverted to CT.

To pay for the trip, Bartz took a loan. Upon his return, he planned to try ZT on a small plot, but a severe frost destroyed his wheat crop and forced him to sell all his equipment to repay the loan. He just kept the ZT planter (it had only scrap value) and was forced to use the technology on his whole farm.[11] Because weed control was difficult with the existing herbicides and equipment, on several occasions Bartz had to use manual weeding on his 650 ha. For many years, Bartz had to face the mockery of his neighbors until ZT became an accepted technology.

The existing planters did not perform adequately in the heavy soils of the Londrina area. In spite of all these problems, Bartz continued to develop the package in collaboration with Derpsch and ICI. Since Bartz had no inclination to promote his ZT experiences, a network to disseminate the package did not emerge. The lack of this network, combined with the technical difficulties delayed the spread of ZT in the Londrina area for several years.

The severe erosion caused major crop losses, forcing many farmers to default on their loans. In the early 1970s, the manager of a branch of the Banco do Brasil[12] in the sate of Paraná convened a meeting of researchers and extension agents to find a technical solution. Following the recipes of the US Soil Conservation Service, they recommended the use of terraces and prepared a chart that related the distance between terraces to the slope of the terrain.

When the farmer Manoel Pereira asked for a loan in 1976, he was told that, according to the chart, his land was too steep for agriculture and that he should revert to cattle. Pereira realized that this would lead to bankruptcy and looked for alternatives. An agronomist suggested that ZT would enable him to increase the distance between terraces. The first trial indicated that ZT was the solution he was looking for. A few neighbors also tried ZT with ICI's help. These farmers were aware of the advances made by ICI and EMBRAPA-CNPT. After 3 years, they felt they had reached a ceiling on their knowledge and needed specialized advice that could not be found in Brazil. In 1979, Pereira and Franke Dijkstra visited the University of Kentucky.

Unlike Bartz, Pereira and Dijkstra were very active in their cooperatives and had a strong commitment to the community. Upon their return, they promoted the creation of the Earthworm Club to exchange ZT

[9] ICI's research strategy was to base its main ZT research team in a country for 2 years where it trained a local team. After that period, the main team moved to a new country and became a consultant to the local team.

[10] Semeato's owner was also a farmer interested in reducing soil disturbance. Eventually, Semeato became the largest manufacturer of ZT planters outside the USA.

[11] This was the first large-scale use of ZT in Latin America.

[12] The Banco do Brasil was then the most important lender to the agricultural sector.

experiences.[13] Many of the cooperative associates were small farmers. Pereira and Dijkstra convinced three neighboring cooperatives to organize a ZT extension program for them. This service later evolved into the ABC Foundation, which conducted both research and extension.[14] The Earthworm Club and the ABC Foundation were institutional innovations that compensated the lack of involvement of the public research and extension services and had a major impact on Brazilian agriculture (see below). The extension efforts were complemented by ICI's sales force that aggressively promoted ZT in all major agricultural states.

A very active collaboration with the University of Kentucky emerged from the visit to the USA. Professors and graduate students from Kentucky often visited Brazil and many cooperative professionals were trained in the US.

By the late 1970s, there were three small networks developing ZT in Brazil. Each network worked relatively independently, even though they were aware of the advances made by the other networks. The linkages were informal contacts between researchers and farmers, and the work of Derpsch and ICI. Both participated in the three networks, but ICI became the hub of the system thanks to its vast amount of resources. The keys to ICI's success were its strong research team, its participatory and multidisciplinary research strategy and a strong sales force that promoted ZT among farmers. The learning routines induced major changes in the habits of researchers, by fostering strong collaboration with equipment manufacturers and farmers.

Even though ICI's goal was to sell paraquat, its business strategy was to separate the development of ZT and provision of technical advise from commercial activities. The rationale was that once farmers realized the advantages of ZT, they would buy the herbicide. This proved to be a major mistake that helped Monsanto to capture the herbicide market created by ZT.

In the early 1970s, IAPAR had a first-class research team. In the late 1970s, the state governor barred the institution from conducting research on ZT on the grounds that it was a technology for large farmers and was promoted by a multinational company. He ordered IAPAR to concentrate on technologies for small farmers. Even though these directives were later reversed, IAPAR required several years to reorganize its ZT research. Eventually, IAPAR developed the first coarse-grain planter for small farmers, which was the base for all following models.

After the success of the Earthworm Club, small groups called Clubes Amigos da Terra (CAT, Friends of the Land Clubs) were created by farmers in the southern states with support from herbicide companies. These groups were a very successful social innovation, because their periodical meetings and stable membership fostered trust and allowed farmers to discuss their technical problems openly. Also, their farmer-to-farmer extension programs were more successful in reaching farmers than the traditional extension routines.

A ZT package adapted to the conditions of the areas close to EMBRAPA-CNPT was developed by the mid-1970s. A limited number of farmers tried the package briefly because weed control was difficult and planters were inefficient. The introduction of a new herbicide (glyphosate[15]) and continuous research by several institutions (public, private, farmers' organizations, and machinery manufacturers) produced a technically efficient package by the end of the 1970s. Adoption, however, was slow because glyphosate was very expensive, making the package economically infeasible.

The second wave of adoption came in the mid-1980s, when the Brazilian government and the World Bank implemented a credit program that promoted watershed management by farmers' groups[16] and the construction of very high terraces. This technology had been developed by technicians from the national extension service who convinced the authorities to finance their construction. These expensive terraces were washed away by the first heavy rains, causing more damage than CT. After a couple of years, ZT became the supported technology.

Soon, the local CATs formed regional ZT associations to reduce the cost of generating and distributing information. Mainly financed and managed by farmers, the CATs received financial and technical

[13] In the interviews, Pereira and Dijkstra stated emphatically that their goals in creating the Earthworm Club were altruistic.

[14] In 1998, the ABC Foundation had a budget of US$ 1 million, totally funded by the cooperatives.

[15] Glyphosate, marketed under the brand name Roundup, was developed by Monsanto and released in 1976.

[16] These groups followed the CAT's model.

support from herbicide companies like Monsanto and ICI.

Compared to paraquat, glyphosate greatly simplified weed control, enabling Monsanto to capture most of the herbicide market. In spite of organizing an active network and of its large investments in creating a market for paraquat and a strong research team, ZT was a commercial failure for ICI. In the late 1980s, ICI cut all research and promotion activities related to ZT.

The third wave of adoption occurred in the late 1980s with the colonization of the Cerrados.[17] The cheap land attracted small farmers from the southern states, who brought with them the ZT experience. However, the Cerrados ecology differed substantially from that of southern Brazil, and the package had to be adapted. Farmers' associations, factories, input suppliers, and individual researchers collaborated in the adaptation process. In spite of the participation of a few researchers, the public research institutions did not participate in the development efforts.

The fourth wave of adoption occurred in the 1990s. Adoption by commercial farmers surged as Monsanto reduced the price of glyphosate from US$ 40/l to <US$ 10/l. Adoption by small farmers in the states of Santa Caterina, Paraná and Río Grande do Sul also exploded thanks to several programs targeted at them. These programs involved complex institutional arrangements, as exemplified by the project METAS.

In 1990, a researcher from EMBRAPA-CNPT and a Monsanto technician conducted a study to identify the causes of low adoption of ZT among small farmers in the state of Rio Grande Do Sul. They identified three factors: lack of a package adapted to local conditions, lack of planters adequate for small farmers and insufficient command of the package by extension agents. Following this diagnosis, Monsanto promoted in 1993 the METAS project which involved five public and private institutions[18] who could develop integrated solutions to the identified problems. Between 1994 and 1997, the area under ZT jumped from 45,000 to 820,000 ha in the project area (90% of the target) and 2,200,000 in the whole state. This success induced other agents to join the program and in the third year the partners were seven private companies, three public research and teaching institutions, the extension service, local planning offices, cooperatives and municipal authorities.

7. Organization of the network that generates ZT

The Brazilian ZT network has evolved into a conglomerate of regional networks that involve farmers, input suppliers, NGOs, foreign aid agencies, public research institutions, funders of research, individual researchers and government agencies. The network has no central decision-making bodies and it self-organizes through the independent actions of its members. In spite of its major success in generating and diffusing ZT, the network efficiency is diminished by several system failures. This section reviews the present state of the Brazilian ZT network.

7.1. Agents

The *Associations of Zero Tillage Farmers* (AZTF) became the hub of the network after ICI ended its ZT activities. The AZTFs play two roles: they reduce the cost of information generation and gathering by exploiting economies of scale, and they fill the gap left by formal research and extension systems who have responded too slowly to the farmers' needs.

The first AZTFs emerged from the altruistic motivations of a few farmers, but soon they became a powerful instrument for the generation and open dissemination of knowledge. Today, there are two clear groups of farmers in these associations: the leadership that still maintains many of the original altruistic goals and the rest of the associates who mainly seek the benefits of accessing useful information at a reduced cost.

Membership of the AZTFs is composed mainly of commercial farmers and funding is contributed by participating farmers and agrochemical companies. Even though the AZTFs distribute freely the information they generate, a substantial number of farmers voluntarily contribute to them. Research and extension in the AZTFs are organized on a regional basis, and are conducted and financed by farmers with support from researchers and input suppliers. The research is

[17] The Cerrados comprises between 180 and 207 million ha in the center and center-west regions of Brazil and is located east of the Amazon rainforest.

[18] Monsanto (herbicides), EMBRAPA (research), Trevo (fertilizers), Agroceres (seeds), and Semeato (planters).

limited to problems that are not science-intensive,[19] does not use a statistical design and is relatively simple and cheap, such as finding better crop rotations.

More formal research will be required to solve the increasingly complex problems that will arise, such as understanding the dynamics of weed and pest populations. However, the AZTFs consistently complained about the lack of response from public research institutions. These associations interact actively with individual researchers but do not lobby public institutions to redirect resources towards ZT because the latter are perceived as too bureaucratic and many decisions are determined outside the institutions. The ABC Foundation conducts formal research in the southern states and partially compensates the weak public efforts.

The AZTFs sometimes invite researchers to lecture or advise on specific problems and organize visits to expositions, meetings and farms, both in the country and abroad. They also organize training programs and field days to share experiences with farmers from other locations and with farmers who do not use ZT.

The main goal of the *agrochemical companies* is to sell their products. In the long run, this depends on the creation of knowledge that increases the sustainability of ZT. For this, they fund and sometimes organize research projects in public research institutions. They supply, on request, their products to the AZTFs and researchers. Often, the projects supported do not have an immediate commercial application, may not be related to the company's product or are aimed at reducing the use of the company's agrochemicals. Again, the output obtained in these projects is knowledge, a public good. The companies interact with farmers, EMBRAPA, state research institutions, AZTFs and universities to identify research needs, but they develop new products through their own research programs. Instead of developing in-house capabilities for agronomic research, herbicide manufacturers rely on the AZTFs and public research institutions.

Manufacturers of planters for commercial farmers have small design teams and conduct in-house development projects; they also organize and fund small projects in public research institutions. Semeato is the only Brazilian planter factory that has a substantial research team. The few multinational factories located in Brazil have their local research teams linked to the teams in the central offices. Manufacturers rely on public institutions for information on relevant agricultural topics (such as soil evolution under different cutting mechanisms), on reverse engineering[20] or on outsourcing for more sophisticated research. These companies do not have formal joint programs with the AZTFs or public research institutions but do have strong links with individual researchers and farmers who try new models.

National public research and extension institutes (*including universities*), as institutions, played a limited role in the development of ZT. They were slow in recognizing its potential and reluctant to recommend it even after widespread adoption had occurred. For example, EMBRAPA headquarters recommend ZT only in 1997, when adoption had surpassed 10 million ha. The two exceptions were IAPAR and EMBRAPA-CNPT. In some cases, authorities strongly opposed ZT and aborted ongoing projects. However, individual researchers from these institutions actively collaborate with the AZTFs. Most of the research in public institutions is in the form of projects initiated and financed by commercial companies or initiated by individual researchers with private financing, usually from input suppliers. Only a handful of research institutions, EMBRAPA in particular, have recently developed institutional policies towards ZT.

National and state governments provided partial and late support to ZT. Their main contribution has been in promoting adoption, not research. *International cooperation agencies* played a key role in the early days of ZT and still conduct research aimed at small farmers. *Small farmers* require a special package, mainly machinery and techniques for soil protection. They have limited resources to fund research, to perform it themselves, to buy it in the form of inputs or advice or to search for information. Because of these constraints, it is not worthwhile for them to form associations. Their lack of resources also hampers their ability to articulate technological and policy demands.

Foreign research institutions and farmers generate information that is useful to local agents. Many

[19] In the sense that they do not require sophisticated equipment, can be designed by professionals without graduate training, and performed by farmers.

[20] It is common for Brazilian, Argentine and American companies to copy innovations introduced by competitors.

Brazilian agents visit Argentina, Paraguay, the USA, and Canada to follow developments introduced there. The activities of American universities are particularly important because they perform science-intensive research that in many cases can easily be transferred to other environments. Recently, multilateral organizations (e.g. World Bank and FAO) established partnerships with the national AZTF to explain ZT (especially, the institutional arrangements) to Asian and African small farmers.

7.2. Interactions

The interactions among agents participating in ZT networks fall into two categories: information exchanges and joint research or extension activities. In addition to the non-traditional interactions described below, input suppliers have the normal market interactions with other agents. Even though market interactions are important in the companies' commercial strategies, they are not relevant for the generation and diffusion of information related to ZT.

Information exchanges for commercial farmers are centered on AZTFs, and for small farmers on NGOs, cooperatives and public institutions. Meetings organized by the AZTFs have been ranked as the most important source of information by all agents, including researchers. The importance of the AZTFs stems from: (1) their role in gathering information from many sources and distributing it freely, and (2) organizing a decentralized research system that uses participatory methods and farmer-to-farmer communication. The AZTFs work efficiently for commercial farmers because they are well funded by farmers and commercial firms. Small farmers, on the other hand, rely on other agents who provide funding and human resources.

Direct contacts between pairs of agents like factories and farmers or groups of researchers are less important channels for information exchanges. Input suppliers (mainly herbicide makers) interact with a multiplicity of agents, fund research, and provide information. Agrochemical companies often exchange non-secret information among themselves, such as topics on the management of experimental stations. Agricultural equipment manufacturers consult individual farmers about new designs.

Interactions among individual public researchers and other agents (researchers from other institutions, farmers or input suppliers) are frequent. Researchers usually search for resources either in kind or money among other agents to compensate diminishing public resources for research, travel and investments in research infrastructure.

7.3. System failures

The recent literature on NIS highlights a new area for public policy: system failures that arise from lack of interaction among agents (OECD, 1999). In the case of the Brazilian ZT network, these include:

1. *The linear concept of science prevailing in most public research institutions*: Until the mid-1990s, most public institutions planned their activities with very little, and in many cases, ineffective interaction with other agents. These institutions sought to maximize academic output without regard for future uses; in other words, their objective was to develop research outputs and then display them in the window for someone to take. The consequence was the establishment of weak information flows between researchers and users, which resulted in the accumulation of unused technologies and lack of social support for research. Researchers and extension agents hesitated to recommend technologies that were not developed by formal research procedures. Furthermore, the structure of incentives in these institutions did not favor innovation and many employees tried to avoid the cost of changing established programs. Despite changes in a few institutions like EMBRAPA, the links between research institutions and other agents are still weak. This lack of response is also evident in most national funding agencies. With only one exception, universities do not have programs on ZT, and in most cases, it is taught as a minor course in conventional curriculums.
2. *Conflicting objectives and instruments in public research institutions*: Public research institutions are going through a transformation process, and its objectives and instruments often conflict. The main features of these changes are: new priority-setting mechanisms that usually rely on more formal procedures; emphasis on diversifying the sources of

funding, which in all cases includes substantial reductions in direct budgetary allocations; greater pressure to generate resources through the sale of goods and services; reductions in the number of researchers and support personnel. The pressure on public research institutions to generate their own resources has forced them to concentrate on producing goods with market value, thus reducing the production of public goods or on research with short-term objectives that responds to political needs.

3. *Insufficient interactions between public research institutions and AZTFs*: This lack of interaction resulted in a belated and weak response from public institutions to a major technological need. If this inadequate response continues, problems that require science-based solutions may become major restrictions to agricultural production under ZT.
4. *Poor collaboration among public research institutions*: Every research institution develops specific areas of expertise. The efficiency of the network could be strengthened through greater interaction among the best teams in each institution. But these interactions are scarce because of lack of incentives to collaborate and insufficient funds.
5. *Micro-management of research programs*: For almost 20 years, ZT was not a priority for public research institutions. In the beginning, individuals who conducted research on ZT were opposed or, at best, ignored by a majority of their peers and authorities. As the trend to centralize priority setting in public institutions strengthened, it has become increasingly difficult for individual researchers to follow lines of research that are not officially recognized.
6. *Few incentives in research and teaching institutions to promote quality, stay up-to-date, or interact with other agents*: In most institutions, promotions are based basically on seniority. In a few institutions, like EMBRAPA, promotions are based on research outputs and management by objectives. This type of incentives are adequate for repetitive tasks, but in the case of uncertain activities (like research), they discourage creativity and risk-taking by researchers. No institution bases incentives on the quality of the research programs or in the interactions with other agents of the innovation system.

8. Conclusions

ZT is the most important agricultural technology adopted in Brazil in the last 50 years. Why could an efficient innovation network emerge around ZT?

1. An agrochemical company had a major interest in developing markets for its new product. Other companies took the risk of developing complementary products (e.g. planters).
2. Commercial farmers had a pressing need to find technological solutions to soil management problems that would allow them to retain soybeans in their rotations. In addition to solving erosion problems, ZT brought large economic benefits to large- and mid-scale farmers. Due to the urgency of the problems, farmers could not rely on traditional research and extension institutions, which were slow in recognizing the importance of ZT.
3. A few pioneer farmers, individual researchers, NGOs, and foreign aid agencies continued to conduct research on ZT despite the major problems they faced in the first years.
4. Since many of the problems were not science-intensive, they were easily understood by farmers who experimented with alternative solutions. The AZTFs enabled them to reduce the cost of generating and distributing information.
5. There was a lack of previous knowledge about ZT and farmers had to create their own channels to exchange information. On the other hand, information channels had been built over the years around most products with a commercial value and agents knew where to look for information when they had problems.
6. Public research institutions and extension services were weak and there was a perception that they could not organize a strong research and extension effort to eliminate soil erosion.
7. For many years individual researchers at public institutions had more freedom to set their own research programs than they have today.

The early development of ZT was characterized by informal collaborations between a few agents, while in the last years the number of agents involved surged. The consolidation of the technological paradigm had three consequences. First, as the network expanded, smaller or regional networks emerged. Second, formal interactions became more common after public sources of funding and public research institutions started their own ZT programs. And third, two parallel research systems emerged. On one side, a relatively weak traditional formal research effort is conducted in several public institutions; on the other side, the AZTFs research system described in this paper. The latter is characterized by the use of participatory research methodologies, farmer-to-farmer extension programs with strong support from researchers, extension agents, and input suppliers, and relatively horizontal flows of information within and between institutions.

The study of the Brazilian experience sheds light on several research policy issues. First, Brazil's experience with ZT cannot be explained by simple theories of technical change, a systemic approach is needed. The early development of modern ZT was supply-pushed,[21] i.e. an agrochemical company (ICI) saw the market potential of a new idea and funded research to develop it before most farmers realized the need to conserve the soil. The first ZT package was adapted to local conditions through the combined efforts of input suppliers, individual researchers, public institutions (IAPAR and EMBRAPA-CNPT), foreign aid agencies and pioneer farmers. After these first results, ZT evolved by the interaction of both supply and demand for technology: after the package matured in the late 1970s, technology development was organized by the AZTFs and suppliers of critical inputs like herbicides and planters. This shows that public research programs based only on technological demands may be too narrow, because researchers have the best understanding of potential uses for their research outputs. Establishment of research priorities should consider supply as well as demand signals.

Second, research agendas cannot be dictated by short-term considerations. Development of the ZT package took more than 12 years. For most of this period, short-term production costs under CT were equal or lower than under ZT. New policies introduced in the early 1990s increased substantially the price of grains relative to the price of agrochemical products. At the same time, Monsanto reduced the price of a key input. Suddenly, ZT became efficient, both from the agricultural and economic points of view.

Third, this particular experience cannot be explained by a linear model of science. Even though development of the first product that enabled ZT (the herbicide) fits this model, the other components of the package were technology developments without an understanding of the scientific processes behind them. For example, even today the changes in soil structure, soil flora and fauna and nutrient mobilization under ZT in different regions are barely understood.

Fourth, the previous two points suggest that research impacts should not be used for research evaluation. If technology development and adoption occurs within a complex innovation system, the impacts cannot be allocated to any single agent but to the whole set; in other words, any impact (or lack of) is not the exclusive result of research. Also, since the timing of the impacts cannot be foreseen, lack of impact may result from technical problems or just from insufficient time for the technology to diffuse.

Fifth, three alternative technologies were developed and tried before soil erosion could be eliminated while maintaining the profitability of agriculture. A priori rejection of duplicate research efforts could have resulted in the adoption of an inferior technology—since alternatives would not have been developed. The uncertainty about the benefits of particular solutions indicates that a certain duplication of research efforts is necessary.

Sixth, the government twice chose to promote inferior technologies with supervised credits. A more flexible technology extension approach would have been more efficient both for farmers and the government.

[21] In the 1950s and 1960s, soil erosion was not considered important in the USA, Europe, and South America.

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