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National, sectoral and technological innovation systems: The case of Taiwanese pharmaceutical biotechnology and agricultural biotechnology innovation systems (1945–2000)

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This paper explores the dynamics of the configuration of the national, the sectoral and the technological innovation systems and defines the configuration of these three innovation systems as the national, sectoral and technological innovation systems (NSTISs). Through comparing the Taiwanese pharmaceutical biotechnology and agricultural biotechnology innovation systems we find that even within the same nation different NSTISs reveal different dynamics, in terms of actors and networks, the application of technology and knowledge and institutions. We conclude that the new research, technology, development and innovation policies should be customized according to the differing dynamics of the NSTISs.

Keywords: innovation system; Taiwan; biotechnology; pharmaceuticals; agriculture.

1. Introduction

Over the last two decades scholars working on innovation systems have established different ways in which to analyze them. The national innovation system focuses on the innovation process within the geographical space of nations (Lundvall 1992; Nelson 1993), while the sectoral innovation system emphasizes the innovation of a particular set of products (Malerba 2002). The technological innovation system uses a specific knowledge field to draw the boundary of an innovation system (Carlsson et al. 2002; Bergek et al. 2008). The configuration of the different levels of innovation systems has been discussed to a certain extent (Markard and Truffer 2008). However, until now the configuration has not been clearly defined and deliberately probed.

Consequently, this paper discusses the configuration of innovation systems at three levels: national, sectoral and technological. We intend to draw the boundary for the ‘new’ innovation system which is embedded in the configuration of the three innovation systems. Moreover, to understand the evolution of the new innovation system we not only examine the components of the innovation system, but follow Malerba’s analysis (Malerba 2005) and explore the changes in the relationships between these components over time. Since national institutions, as generally acknowledged by the literature about innovation systems, play an essential role in shaping and fostering the development of an innovation system, in this paper we will pay special attention to the role of national institutions in the development of new innovation systems.

The government's research, technology, development and innovation (RTDI) policies, which are special forms of national institutions and particularly serve the national technological and industrial concerns, center our discussion on the national institutions.

The Taiwanese biotechnology industry and the two sectors which adopt biotechnology (i.e. pharmaceuticals and agriculture) provide an interesting case for our discussion. Historical records for the period 1945–2000 in Taiwan clearly show the process through which the three innovation systems, i.e. the national innovation system of Taiwan, the sectoral innovation systems for pharmaceuticals and agriculture, and the technological innovation system for biotechnology, gradually configured each other. Indeed, the pharmaceutical and the agricultural sectors not only possessed contrasting opportunities for the development of biotechnology, but were extensively shaped by different national institutions. The pharmaceutical sector, which was mainly composed of local enterprises, that were small- and medium-sized enterprises (SMEs), only adopted biotechnology after the 1980s. The Taiwanese government shaped the sector through its policies on pharmaceuticals and biotechnology. On the other hand, the agricultural sector, which was dominated by public research organizations, started to adopt biotechnology before 1945. The Taiwanese government supported the sector through agricultural policies, which were not considered part of the biotechnology policies. In summary, within the same national border of Taiwan different configurations of the three innovation systems show different dynamics, which are worth further discussion.

To set up a more profound discussion of the configuration of the three innovation systems we structure the rest of this paper as follows: Section 2 reviews the literature on innovation systems. On the basis of the literature we conceptualize the configuration of the three innovation systems. Section 3 analyzes the evolution of the Taiwanese innovation systems for biotechnology, pharmaceuticals and agriculture through the lens of the configuration of the three innovation systems. Section 4 discusses our conceptual and empirical contributions, draws conclusions and makes suggestions for future research.

2. Literature review and the configuration of the innovation systems

The conception of the configuration of the three innovation systems is established on the theoretical foundations of different system approaches. Since each system approach has different focuses, before we build the new concept for an innovation system we first review the key concepts of each approach, as well as their analysis of the role of national institutions in the development of an innovation system.

A national innovation system focuses on the national development of technology and industries. The national frontiers draw the boundary of an innovation system. The institutional actors, such as firms and industrial laboratories, universities and government laboratories, and their networks constitute the national innovation system (Nelson and Rosenberg 1993). Through comparing the similarities and differences across countries the approach illustrates how the institutions and mechanisms of a nation support technological and industrial innovation within its borders (Nelson and Rosenberg 1993; Edquist and Hommen 2008). From Freeman's perspective (1987) research, technology, development and innovation (RTDI) policies extensively shape the national system of innovation. The OECD (1999) also claims that RTDI policies should match the development of the national system.

The sectoral innovation system recognizes a system as a set of products which are developed in a global context. A sectoral innovation system, as analyzed by Malerba (2004), should have a set of specific knowledge bases, inputs and demands. A group of actors in the system carry out market and non-market actions for the creation, production and sale of the products. These actors interact through communication, competition, cooperation and commands, and the actors' networks are shaped by institutions, such as national institutions. Indeed, actors and networks, knowledge and technology, and institutions are the three blocks of a sectoral innovation system. National institutions, from the perspective of Malerba (2002), should match the sectoral innovation system within the national borders.

The technological innovation system is defined in the sense of a knowledge field which has developed globally. As speculated by Carlsson et al. (2002), within a particular knowledge field the actors, including the buyers and sellers, of a dynamic network interact in a specific economic or industrial arena which is under specific institutional infrastructures. The interactions of the actors in the network are both market and non-market. Technological generation, diffusion and utilization are at the core of the analysis. Comparing the energy innovation systems of Germany, Sweden and the Netherlands, Jacobsson and Bergek (1998) concluded that national institutions, especially government policies, do influence the performance of a nation's technological innovation system.

According to the literature an innovation system is composed of actors and networks, technology and knowledge, and institutions. However, because a different system approach uses different criteria to draw the boundary of an innovation system, the components and their interactions in the configuration of the different levels of innovation systems remain unclear. Bergek et al. (2008) have only specified that a technological system may be a sub-system of a sectoral innovation system or may cut across several sectoral innovation systems. Malerba (2004)

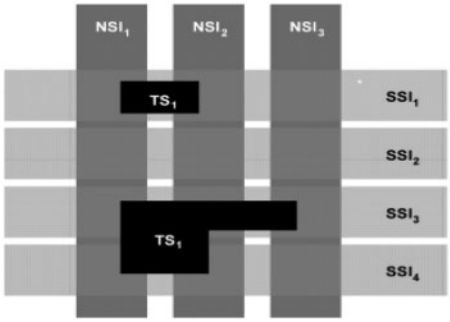

Figure 1. Potential relationships between national (NSI) and sectoral (SSI) systems of innovation and a technological innovation systems (TS).
Source: Markard and Truffer (2008).

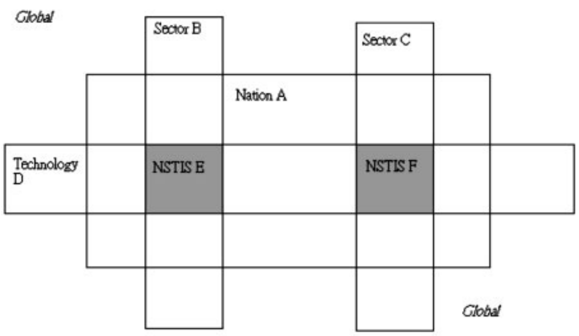

Figure 2. Relationship of national, technological and sectoral innovation systems and NSTIS.

has also tried to link the relationships within a sectoral innovation system to a country's international performance, as well as a sector to the technological opportunities which can be mobilized to develop new products and processes for that sector. Markard and Truffer (2008) made one of the first attempts to concretely show the configuration of the three innovation systems within one diagram. From their perspective (see Fig. 1), a national system is delineated on a spatial basis, while a sectoral system usually crosses a geographical boundary, and a technological innovation system typically crosses both geographical and sectoral boundaries. Nevertheless, Markard and Truffer did not go beyond their diagram to concretely define and explain the intersections between the three innovation systems.

Based on Markard and Truffer's diagram (Markard and Truffer 2008), we redraw the relationships of the three innovation systems (see Fig. 2) and define the configuration of the three innovation systems as the NSTIS. We assume that the system exists within a particular national border and is embedded in the global context. The actors within the system, such as institutional actors, use the knowledge of a particular technological field to produce a set of particular products. The actors within the system carry out market and non-market interactions in order to generate, diffuse and utilize the knowledge of a particular technological field to create, produce and sell a particular set of products. The interactions and networks between the actors are shaped by national institutions. The national government plays an essential role in establishing national institutions. To sum up, an NSTIS, as the three innovation systems, is composed of actors and networks, technology and knowledge, and institutions. The components of the system are shaped by national institutions.

We choose the Taiwanese biotechnology and two biotechnology-related sectors as an empirical case because that case is seldom discussed in the existing literature. Modern biotechnology, as defined by Laage-Hellman et al. (2004), is the biotechnology developed in the post-genetic engineering era in the 1970s and comprised of a broad range of knowledge fields.[1] The biotechnology developed before the post-genetic engineering era is defined in this paper as traditional biotechnology. While the majority of the existing literature on modern biotechnology focuses on the empirical experiences of European countries and the USA (McKelvey et al. 2004; Brink et al. 2004; Senker 2004; McKelvey 1996; Kaiser and Prange 2004; Geseisk 2000; Torgersen and Bogner 2005; Boschert and Gill 2005), only a few papers discuss the development of biotechnology (both traditional and modern) in Taiwan (Dodgson et al. 2008; Wong 2005). Indeed, the existing literature considers Taiwanese biotechnology to be a 'new sector' which has only emerged in the last ten years and is strongly guided by a 'set of' government policies. Nevertheless, as we will show in Section 3, Taiwan adopted traditional biotechnology before 1945 and adopted modern biotechnology as early as the 1980s. Biotechnology is not a sector but a technology which is adopted by at least two sectors in Taiwan, i.e. pharmaceuticals and agriculture.[2] Different sectors have their own unique history and use a unique mode to absorb biotechnology, which differs from the experiences of Western countries. Moreover, the Taiwanese government has not implemented a 'set of policies' towards biotechnology, but has adopted different sets of policies towards pharmaceutical biotechnology and agricultural biotechnology. The evolution of biotechnology and the two sectors before 2000 in fact deeply influences the development after 2000. Since the history of biotechnology and the two sectors in Taiwan is missing, we select Taiwan as our empirical case and focus on the development in the period 1945–2000. By analyzing the historical archives, such as government documents and the historical records of the institutions embedded in the innovation systems, we will discover how the technological innovation system for biotechnology gradually emerged with the Taiwanese national innovation system, as well as the sectoral innovation systems for pharmaceuticals and agriculture.

3. The Taiwanese pharmaceutical biotechnology and agricultural biotechnology innovation systems

This section analyzes the history of biotechnology and the two sectors in Taiwan through the lens of the NSTIS. We especially focus on the components of each NSTIS and the changes in their interactions over time. In order to give a relatively precise view to the long history, we particularly single out the years 1945 and 1982 as milestones. 1945 was the year when Japan returned Taiwan to the Republic of China (ROC).[3] After 1945 Taiwan started to have an independent history. The Taiwanese government announced its first biotechnology policy, the 'Eight Key Industries' in 1982. After 1982, Taiwan started to have a biotechnology policy. We discuss the evolution of the pharmaceutical biotechnology innovation system in Section 3.1 and the evolution of the agricultural biotechnology innovation system in Section 3.2.

3.1 The evolution of the Taiwanese pharmaceutical biotechnology innovation system

3.1.1 Pharmaceutical companies: networks and knowledge base. Pharmaceutical technology was originally introduced to Taiwan by Japan. In 1931, some Japanese pharmaceutical companies set up factories in Taiwan to produce pharmaceutical intermediaries and supply the demands of the Japanese army. When Taiwan was returned to the ROC in 1945, there were 312 factories all over the island (Zheng 2001: 195). The government of the ROC then unified the 312 factories into one national pharmaceutical company (Taiwan Pharmaceutical Company). Later, because of financial deficits, the Taiwan Pharmaceutical Company gradually sold all of its factories to different private firms (DCB 2003: 208). The sector which was once institutionally unified by the public sector was then split by the private companies.

After the Japanese colonization, some local private pharmacies started to use rough facilities to synthesize simple pharmaceutical intermediaries in their backyards (Zheng 2001: 196). These small local pharmacies gradually developed into small family-operated factories. Moreover, since the government of the ROC moved its central government from China to Taiwan in 1949, some Chinese pharmaceutical companies also relocated their factories to Taiwan around 1950. Both the original Taiwanese companies and the newly arrived Chinese companies had limited numbers of employees and capital with which to develop complex products, but they manufactured low-end intermediaries that were highly similar to each other (Ding 2001: 232). Besides manufacturing intermediaries, some local firms imported higher-end intermediaries from countries, such as Japan and Germany, and processed them into generic medicines. However, the products of these companies overlapped. The knowledge base of all these firms was chemical engineering rather than biotechnology. Even if modern biotechnology was developed in the USA in the 1970s, these companies did not adopt any modern biotechnology in their products. In 1982, to fit the new 'Good Manufacturing Practice' regulations announced by the government, the manufacturing facilities of local SMEs were upgraded (Zheng 2001: 193, 229). However, because of their small size, these companies were unable to innovate or to export their products. Instead they competed with each other in the domestic market on the basis of price. Until 2000, knowledge transfer and collaboration between companies were minimal. Competition was the mainstream for the interactions between these companies (DCB 2003: 207).

Multi-national pharmaceutical giants who were attracted by the government's policies of foreign direct investment (FDI) and the low cost of manufacturing began to invest in Taiwan in the 1960s. Most of these multi-national corporations (MNCs) were from Japan and the USA, such as Takeda Pharmaceuticals (from Japan) and Pfizer (from the USA). The MNCs brought advantageous manufacturing technologies to Taiwan, particularly the technologies of chemical engineering for pharmaceuticals. In the 1980s, with advantageous technologies and marketing capabilities, MNCs shared more than 50% of the domestic market (Zheng 2001: 203). Nevertheless, since the 1990s, because of the rising cost of manufacturing in Taiwan and the policies of free trade in pharmaceuticals, pharmaceutical MNCs gradually sold their manufacturing facilities to local companies (DCB 2003: 209). After these sales, MNCs kept only their marketing divisions in Taiwan to deal with the business of importing medicines, and local SMEs gradually became the main force in manufacturing. Yet, as shown by the statistical data in 1995, the sales of local SMEs only accounted for 31% of the domestic market, while MNCs accounted for 38%, and the imported medicines had 31% of that market (Zheng 2001: 194).

A very minor but important sub-sector of the pharmaceuticals was Chinese herbal medicine, and local SMEs were the leaders in this sub-sector. In fact, during the colonization by Japan, for political reasons, the development of Chinese herbal medicines was strictly constrained. Only after 1949, when some Chinese herbal pharmacies followed the government of the ROC and moved their pharmacies from China to Taiwan, did Taiwan start to use Chinese herbal medicines. Later, these Chinese herbal pharmacies gradually set up their own herbal factories (DCB 2003: 219).

Before the 1980s, the main business of the herbal factories was to use modern machinery to process the herbs to be customized into Chinese herbal medicines.[4] Herbs were decocted, pounded and kneaded by modern machinery. Several herbs were combined together in fixed proportions and became one medicine. Because of a lack of extraction technologies, these herbs were usually used in their entirety. Furthermore, the functions of each herb were not surveyed in detail by scientific methods. The knowledge accumulated about the functions of each herb was based on the records of traditional Chinese pharmacopoeias. The products produced by the herbal factories were the herbal medicines which were well documented in the pharmacopoeias rather than innovative ones. The quality controls in these herbal factories were not consistent. The majority of these factories targeted the domestic market and rarely exported their products (DCB, 2004: 100).

Only after the 1980s, was modern biotechnology gradually adopted by the companies producing Chinese herbal medicines. While the majority of companies still focused on manufacturing and followed the Good Manufacturing Practice rules to upgrade their machinery facilities, in the 1990s, some of these companies started to establish networks with academics in order to develop new herbaceous medicines. At the time, strict clinical trials were gradually applied for the development of new herbaceous[5] medicines. Since the Taiwanese government had no regulations to review the licensing of the new medicines, all the companies producing Chinese herbal medicines followed the regulations of the US Food and Drug Administration (FDA). Each traditional Chinese herbal medicine was made by combining different herbs. To comply with the US FDA regulations, each new herbaceous medicine was made by a single composition extracted from a particular herb. Indeed, the companies that invested in the innovation of Chinese herbal medicines only carried out detailed research related to these single herbal extracts. Modern biotechnology was applied to extract the functional ingredients of the herbs. Furthermore, modern biochemistry, which was introduced by scientists trained in the USA, was applied for the deeper analysis of the medical functions (e.g. chemical activities) of single herbal extracts. But no new herbaceous medicines were successfully developed before 2000 (DCB 2003: 224–7).

3.1.2 Universities and the accumulation of knowledge. The main role of universities until the end of the 1980s was to train qualified pharmacists. The Taiwanese branch of the Imperial University, which became the National Taiwan University after 1945, was the first and only university in Taiwan during the Japanese colonization. Yet there was no pharmaceutical college in the university and no other academic institution to train pharmaceutical experts. Indeed, the first generation of pharmacists was the Taiwanese students trained in Japan. These Taiwanese pharmacists introduced pharmaceutical knowledge from Japan to Taiwan. Later, in the period 1949–66, while some Chinese universities followed the government of the ROC to Taiwan and rebuilt their campuses in the island, some Taiwanese universities also set up locally.[6] Until the late 1970s, there was a total of six pharmaceutical colleges in the universities of Taiwan (Zheng 2001: 3). However, their main purpose was to train qualified pharmacists. Pharmaceutical research in universities was rare, and only some particular universities, such as National Taiwan University, did some initial research into chemical medicines and Chinese herbal medicines (National Taiwan University 2000: 49). Only in the early 1990s, with the gradually developed environment for pharmaceutical research, did some universities, like the National Taiwan University, started to provide postgraduate degrees in pharmacology and train pharmaceutical researchers (Zheng 2001: 80, 81).

Modern biotechnology was introduced to Taiwan's universities in the 1980s by a group of young scientists. Unlike the old generation of pharmaceutical experts, who were trained by the Japanese system, the younger generation was trained in the USA. These young scientists transferred modern pharmaceutical biotechnology, such as molecular biotechnology and biochemistry, from the universities of the USA to Taiwan and soon became the leaders of the pharmaceutical colleges. Because of the participation of these young scientists, modern biotechnology was quickly dispersed among the universities and extensively deepened the level of pharmaceutical research for small molecular medicines and Chinese herbal medicines (Zheng, 2001: 242).

Nevertheless, from the 1980s until 2000, the networks between the researchers and between universities and pharmaceutical companies were not fully established. The research interests of individual scholars determined the research topics. Collaborations between different academics were not frequent. Even though the scientists had related research interests, they had very limited cooperation with each other. Moreover, universities had limited interactions with pharmaceutical companies. Due to the regulations concerning academics,[7] interactions between universities and pharmaceutical firms were forbidden. In fact, the main occasion for academics to practice their knowledge was to support the government in drawing up regulations in order to control the qualities of the pharmaceuticals. For example, some scientists of Chinese herbal medicines were funded by the government to survey the herbs of Taiwan. But such surveys were merely to serve policy expectations rather than to lead to commercialization (Zheng 2001: 203, 242).

The public research organizations play an intermediary role between universities and pharmaceutical companies. Since the universities were not supposed to directly interact with firms, the Development Centre of Biotechnology (DCB), a public research organization, was set up in

1984 to apply the research into small molecules from the universities to develop new chemical medicines and then transfer such technologies to local firms. However, because the majority of pharmaceutical companies that manufactured pharmaceutical intermediaries or generic medicines were unable or unwilling to develop new medicines, the DCB gradually became the research center for developing pharmaceutical intermediaries and transferring the technology of chemical engineering to pharmaceutical manufacturing (Ding 2001: 229). The Industrial Technology Research Institute, another public research organization, also helped local SMEs upgrade their manufacturing facilities in order to comply with the Good Manufacturing Practice regulations. But until the late 1990s, there was no institution which could transfer pharmaceutical biotechnology from the universities to pharmaceutical companies.

3.1.3 National institutions: Pharmaceutical and biotechnology policies. The Taiwanese government did not strategically promote a 'set of consistent policies' to foster the development of pharmaceutical biotechnology. Instead, each policy directed towards pharmaceutical biotechnology had its own historical background and changed with the evolution of pharmaceuticals and biotechnology. The Eight Key Industries policy, which was the first biotechnology policy announced in 1982, should be regarded as an important milestone in the change of policies. Before 1982, the main purpose of policies was to encourage and to control the manufacturing activities of the pharmaceutical sector. Thus regulation and FDI policies were very important. After 1982, as policies gradually turned to encouraging innovation in the pharmaceutical sector, R&D policies became more and more significant. However, as a milestone, the Eight Key Industries itself was only a general policy announcement. Besides recognizing biotechnology as one of the eight key industries in which the government should invest more resources, there was no other concrete policy promoted under the framework of the Eight Key Industries. Furthermore, according to the Eight Key Industries policy, the development of biotechnology was almost equal to the development of the pharmaceutical sector whose knowledge base was chemical engineering rather than biotechnology (MOEA 2010).

Policies of regulation, FDI and R&D were directed towards the pharmaceutical biotechnology innovation system. The Law of Pharmaceutical Affairs was passed in 1970 and remained the most important regulation controlling the manufacture of medicines until 2000. The Good Manufacturing Practice regulations were launched in 1982 to force the local SMEs to upgrade their manufacturing capabilities. In 1950, the government launched the 'Statute for Encouraging Foreign Direct Investment' (abolished in 1990) and gave pharmaceutical MNCs tax exemptions if they manufactured their pharmaceutical products in Taiwan or transferred manufacturing technologies based on chemical engineering to local companies (Zheng 2001: 202). In terms of R&D policies, fundamental biological and pharmaceutical research in universities was continuously funded, and the DCB was found in 1984 to transfer pharmaceutical technology of chemical engineering from the universities to pharmaceutical companies (DCB 2010). However, there was no R&D policy to encourage universities to transfer pharmaceutical biotechnology to companies, and before the late 1990s, there was no particular target for the funding of R&D policies. Only after 1998 did the government start to recognize Chinese herbal medicines as the backbone of the pharmaceutical sector. From the perspective of the government, since the knowledge accumulation of bio-pharmaceuticals in Taiwan was too weak to compete with developed countries, Taiwan should fully activate its strong knowledge base of Chinese herbal medicines to take advantages in the pharmaceutical sector. The R&D policies thus turned to encouraging the development of new herbaceous medicines (NSC 2010).

To sum up: before the late 1990s, the government did not have specific policies to encourage the development of modern pharmaceutical biotechnology. It only had policies to foster pharmaceutical chemical engineering. Only in the late 1990s did the government start to support the development of modern pharmaceutical biotechnology through supporting the innovation of new herbaceous medicines.

3.2 Evolution of the Taiwanese agricultural biotechnology innovation system

3.2.1 Agricultural public research organizations and private companies. The institutions for the innovation of seeds were originally set up by the Japanese government and further developed by the government of the ROC after 1945. The research organizations of the system of agricultural experiments stations (ASs), which included the Agriculture Research Institute, were the most important organizations for seed innovation. These research organizations were fully funded by the Japanese government during the Japanese colonization and then by the government of the ROC. Indeed, during the Japanese colonization, in order to feed the population of Japan, the Japanese government introduced Japanese rice seeds to Taiwan. The Ass research organizations used the traditional biotechnology of hybridization to improve the genes of Japanese rice with the genes of Japonica, a Taiwanese rice which looked and tasted like Japanese rice but grew well in the subtropical climate of Taiwan. This was representative of the new rice. In addition to their work on rice, the experts at the ASs also carried out genetic research on subtropical fruits and vegetables, such as sugar cane and tea (Su 2004: 18). Before 1945, the Japanese scientists who had led the ASs had trained some Taiwanese experts within these organizations (Lin 1995: 2). After 1949, with the exception of the original Taiwanese experts, some Chinese experts who followed the government of the ROC and migrated from mainland China to Taiwan replaced the Japanese scientists and became the senior researchers in the ASs. The knowledge about hybridization which had been accumulated by the Japanese scientists was then further developed by the Taiwanese experts, especially in rice research (Su 2004: 18).

When the new seeds had been developed by the ASs they were then passed to the farmers' association, which had been founded by the Japanese government to control the production activities of farmers. One of its main responsibilities was to distribute the seeds from the ASs to individual farmers. After 1945, the government of the ROC replaced the Japanese government in governing the farmers' association. Every farmer had a small farm which was intensively cultivated. The farmers obtained seeds from the farmers' association free of charge. The innovation institutions regarded the farmers as mere producers, who only had only limited knowledge about cultivation. Their experience was seldom fed back to the ASs. The system expected the experts at the ASs to understand the processes involved in cultivation and to improve the next generation of seeds. Furthermore, before the 1980s, most of the crops, especially rice, were exported to foreign markets. Farmers who served the foreign markets only obtained rewards from the sales of their harvests. However, the rewards for farmers were only sufficient for their survival. They were not sufficient for them to reinvest in seed innovation (Liu 1996: 188).

The institutions for seed innovation remained almost the same until 2000. However, the introduction of modern biotechnology in the 1980s extensively changed the knowledge and technology used for seed innovation. The modern biotechnology of genetic modification was introduced to the ASs through a group of Taiwanese scientists who were trained in the USA. While the traditional biotechnology of hybridization was retained for the innovation of seeds and expanded to the innovation of new species of livestock, such as farm animals and aquaculture, the modern techniques of genetic modification were adopted to improve the genes of particular seeds, such as the seeds of subtropical fruits. In 1997, the genetically modified (GM) papayas which were developed by the Taiwanese scientists and successfully grown in the trial fields were milestones in the development of genetically modified organisms (GMOs). In fact, all the papayas were cultivated in the subtropical climate of the south of Taiwan. Since the old types of papayas were easily infected by parasites, their genes were modified to be parasite-resistant. Nevertheless, because of the Taiwanese government regulations, even though the GM papayas were successfully developed, they were not allowed to be cultivated in the normal farms (Science and Technology Research and Information Center, 2005: 31, 33). Furthermore, all the new hybrid seeds and livestock innovated by the ASs were not commercialized but were transferred to the farmers' association, which then distributed them to the farmers free of charge.

There were some small local private seed companies surrounding the Ass which played supplementary roles in the innovation of seeds. These companies usually focused on specific types of seeds and sold these seeds to farmers. For example, the Known-You Seed Cooperation had specialized in and sold watermelon seeds since the 1960s (Cai 2007). The technology used by these private companies was the traditional biotechnology of hybridization which was also used by the ASs. Only in the 1990s did some local SMEs start to transfer the modern biotechnology of genetic modification from academic institutions and developed GMOs, especially non-edible GMOs. For example, Taikong which was a trade company selling ornamental fish has worked with the National Taiwan University to develop GM ornamental fish since the 1990s (Taikong 2010). However, before 2000, the private companies had not successfully developed any new GMOs. Moreover, throughout Taiwanese agricultural history, MNCs such as Monsanto, have not played any role in seed innovation in Taiwan.

3.2.2 Universities and their networks. Universities undertook fundamental agricultural research and applied their research through the network with the ASs. The network between universities and the ASs was established before 1945. Until the 1970s, the agricultural college of National Taiwan University was the most important academic institution carrying out fundamental agricultural research, and the ASs were the most important research institutions carrying out applied agricultural research. The headquarters of the ASs was first built next to National Taiwan University. Through the flow of personnel, knowledge of the traditional biotechnology of hybridization was transferred between the university and the ASs. In fact, many graduates from the National Taiwan University took important positions in the ASs (Su 2004: 18). In the early 1970s, when the headquarters of the ASs was moved next to Chung-hsing University, the agricultural college of that university, which was once an agricultural vocational school, became another important academic institution for agricultural research (Lin 1995: 3; Su 2004: 18).

A group of Taiwanese scientists trained in US universities introduced modern molecular biotechnology to Taiwanese universities in the 1980s. Molecular biotechnology greatly increased the depth of basic agricultural research, especially in genetic modification. However, because a network between universities was not established, the research topics were usually chosen according to the research interests of individual scholars. The topics studied frequently overlapped and there was very limited coordination between the research teams (Su 2004: 18, 20).

Until 2000, most results of modern biotechnology research done by the universities were transferred to the ASs for further application (Su 2004: 18, 20). The ASs created a microbial gene bank, the Agriculture Gene Resources Center, in order to store the genes of hybrid and GM seeds. But, only some of the seeds from the Agriculture Gene Resources Center were commercialized. While the hybrid seeds were disseminated to farmers without charge, the GM seeds were stored at the ASs and were not allowed to be planted in the normal farms. Even though they held a rich database of genetic resources, the ASs merely charged the cost of handling and shipping for their services (Su, 2004:18). Indeed, until the 1990s, the modern biotechnology innovated by the universities was only occasionally transferred to particular agricultural companies, such as Taikong.

3.2.3 National institutions: Agricultural policies. The Taiwanese government supported the development of agricultural biotechnology through its agricultural policies. The purpose of these policies changed dramatically in the 1980s. Before the 1980s, the agricultural products were export-oriented. The main purpose of the agricultural policies at the time was to direct the agricultural sector to maximize the production of agricultural products, especially the primary productions of rice and sugar cane, in order to earn large amount of foreign currencies. The majority of foreign exchanges were used to support the development of manufacturing industries, particularly the information and communication technologies (ICT). Only after the 1980s, when the manufacturing industries were well developed and agricultural products were no longer exported, did the policy objectives of the agricultural policies turned to upgrading the farmers' living standards (Chang 1982: 238–9). Even though biotechnology was intensively used by the agricultural sector, when the first biotechnology policy, the Eight Key Industries, was announced in 1982, agricultural biotechnology was not recognized as a part of the development of biotechnology. Indeed, since the 1980s, compared with the prosperous ICT industries, the agricultural sector was gradually recognized as the sector with low productivity. While the government allocated considerable amounts of resources to support ICT, the resources allocated to the agricultural sector were relatively limited.

The two main agricultural policies promoting agricultural biotechnology innovation system were agricultural R&D and regulation policies. For agricultural R&D policies, the government continued funding fundamental agricultural research in the universities and applied research in the ASs. Before the 1980s, research into traditional biotechnology was funded in order to increase the productivity of the agricultural sector, and after the 1980s, research in modern biotechnology was funded merely to increase the farmers' welfare (Chang 2004: 151). Treating agricultural R&D policies as a type of welfare policy, modern agricultural biotechnologies innovated by universities and public research organizations were not commercialized but were transferred to farmers on a non-profit base. In the 1990s, when the Taiwanese government was preparing to participate in the World Trade Organization and to open its domestic market for foreign agricultural products, the R&D funding for modern agricultural biotechnology was even slightly decreased (Wong 1998: 115), and at the same time, the Farmers' Insurance was launched (CLA 2010).[8] Another important agricultural policy promoted by the government was agricultural regulation. Before the 1980s, there was no policy regulating the innovation of seeds. With the development of GMOs in the 1980s, 'Genetic Modified Safety Rules' were implemented in the labs. Yet, besides field trials, none of the GM seeds were allowed to be traded in the domestic market. Moreover, until 2000, there was no regulation for non-edible GMOs. Therefore, non-edible GMOs, such as GM ornamental fish, could be traded in the domestic market without permission.

In sum, besides its agricultural policies, the Taiwanese government did not have particular policies to support the development of agricultural biotechnology. Even though the technological level of the agricultural biotechnology innovation system was very high, due to the government's policies, these biotechnologies were seldom commercialized.

4. Discussion and conclusion

The Taiwanese pharmaceutical biotechnology innovation system and agricultural biotechnology innovation system reveal different dynamics. The three innovation systems, i.e. the Taiwanese national innovation system, the two sectoral systems of pharmaceuticals and agriculture, and the technological innovation system for biotechnology, were configured differently. Different NSTISs not only had different components, but also evolved differently. Based on the empirical case of Taiwan we raise four interesting issues which deepen our understanding of the concept of NSTISs.

Firstly, the actors and networks of different NSTISs may differ from each other and evolve differently over time. As shown by the case of Taiwan, in the pharmaceutical biotechnology innovation system local SMEs led the innovation and manufacturing. MNCs were only involved once in the manufacturing activities of the system and then gradually withdrew their investments in the 1990s. After that there were fewer and fewer large firms involved in pharmaceutical manufacturing. Competition was the main mode of interaction between local SMEs. Because of the regulation of human resources in universities the networks between universities and pharmaceutical companies were not clearly established. Only after the 1980s did some Chinese herbal medicine companies occasionally cooperate with the universities to develop new herbaceous medicines. And in the majority of cases it was the public research organizations, such as the DCB, which played an intermediary role between the universities and pharmaceutical companies. However, in the agricultural biotechnology innovation system the public research organizations, the ASs, were the foundations on which innovation was built. Local private agricultural SMEs only played a supplementary role in innovation and targeted those products which were not yet innovated by the public organizations. Universities were mainly involved in the innovation through the network with the public research organizations. Only in the 1990s did some universities occasionally transfer modern biotechnology to agricultural SMEs. In brief, within the same nation different NSTISs may involve different groups of actors, and the networks of the different groups of actors may not only be quite distinct, but may also change differently over time.

Secondly, different NSTISs may adopt the same knowledge base to develop different products and provide contrasting opportunities for the development of the knowledge. In the Taiwanese pharmaceutical biotechnology system the main knowledge base of both local SMEs and MNCs was chemical engineering. The system only adopted modern biotechnology and did not produce any opportunities for the development of traditional biotechnology. Modern biotechnology was only introduced to the system after the 1980s and was used to extract and analyze the medical ingredients of herbs. Modern biotechnology was integrated with the traditional Chinese knowledge of herbal medicine to produce new herbaceous medicines. In contrast, in the agricultural biotechnology system both the public research organizations and private SMEs adopted biotechnology as their main knowledge base. The system provided the chance for the development of both traditional and modern biotechnology. The traditional biotechnology of hybridization had already been used before 1945 in order to improve the genes of rice and subtropical vegetables and fruits. Since the 1980s the modern technique of genetic modification was applied to improve the genes of subtropical fruits (such as papayas) and non-edible organisms (such as ornamental fish). In summary, the two NSTISs in Taiwan used different processes to adopt biotechnology and produced different sets of products.

Thirdly, the national institutions which shape various NSTISs may differ and may each have a characteristic path of co-evolution with the NSTIS. In the case of Taiwan there is no 'set of national institutions' directed towards the overall national innovation system. The two NSTISs were shaped by different sets of policies. The policies directed towards the pharmaceutical biotechnology system were regulations, FDI and R&D. Before the 1980s, while pharmaceutical manufacturing was the main activity of the system, the main policies were regulation and FDI, which aimed to control the manufacturing facilities and the quality of the medicines. After the 1980s, when the pharmaceutical companies gradually adopted biotechnology to innovate new herbaceous medicines, R&D policies became more and more important. Indeed, the Eight Key Industries, the first biotechnology policy, targeted the development of the pharmaceutical sector, rather than biotechnology. Whilst the public organizations such as the DCB transferred technologies to pharmaceutical companies, they supported pharmaceutical companies to adopt more chemical engineering rather than biotechnology. On the other hand the agricultural biotechnology system was only supported by agricultural policies. Before the 1980s, while agricultural products were exported, the agricultural R&D policies focused on the quantity of agricultural products. However, after the 1980s, once the agricultural products only served domestic demands, the government promoted agricultural R&D and regulation policies, merely to increase the welfare of farmers or to control domestic food safety. Even though the system certainly adopted biotechnology for innovation, the commercialization of agricultural biotechnology was not encouraged by policies. In summary, the development of the NSTIS is deeply shaped by national institutions such as national RTDI policies. The national institutions directed towards different NSTISs may differ and co-evolve with different NSTISs over time.

Our final issue is the implications of RTDI policies. With the new concept of an innovation system, the NSTIS, the RTDI policies which can appropriately foster the development of an innovation system, can be reanalyzed. As shown above different NSTISs may have different actors and networks, as well as different applications of a particular technological field for different sets of products. Thus, appropriate RTDI policies which foster the development of NSTISs should cluster the network of actors, support the underlying logic of knowledge accumulation and exploitation in a particular technological field, and encourage the production and innovation of a particular set of products. Indeed, new RTDI policies should be customized to deliberately match the different dynamics of different NSTISs, rather than the dynamics of the national, sectoral or technological innovation system alone. Moreover, since the national institutions of different NSTISs may have different origins, the new RTDI policies should take account of the different historical backgrounds of different policies. In the case of biotechnology, a government should have different sets of policies for the development of pharmaceutical biotechnology and agricultural biotechnology. Since each NSTIS is unique, RTDI policies copied from foreign countries or copied from another NSTIS will find it very difficult to appropriately support the development of a specific NSTIS. However, in this paper we have not answered the question: 'how' could a government make appropriate RTDI policies to foster the development of NSTISs? The question should be further analyzed in future research.

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Notes

1. These knowledge fields include: DNA (the coding), proteins and molecules, cell and tissue culture and engineering, process biotechnology, and sub-cellular organisms (Laage-Hellman et al. 2004).
2. The medical device sector also adopts biotechnology through the development of bio-chips whose knowledge base is across electronic engineering and biotechnology (Dr. Chip 2010). However, since biochips are very minor in the sector, we do not discuss the development of medical devices in this paper.
3. Internationally, the official name of Taiwan is the Republic of China (ROC). In the years 1890–1945, Taiwan was colonized by Japan. After World War II, in 1945, as a defeated nation, Japan was forced to return Taiwan to the government of the ROC. However, soon after Taiwan was returned, the government of the ROC lost its battles with the Chinese Communist Party in China. In 1949, the Chinese Communist Party successfully set up the central government of the People's Republic of China (PRC) in Beijing, China. In the same year, the central government of the ROC was moved to Taipei, Taiwan.
4. The Chinese have used herbs as medicines and health food for five thousand years. A rich knowledge of herbs was accumulated. The knowledge also spread to adjacent countries, including Japan and Korea. Compared with herbal medicine, the Chinese have only used Western pharmacology for a hundred years. The traditional Chinese herbal medicines were usually compound prescriptions. In other words, multiple herbs were used for one disease. Both the medical functions of single herbs and particular prescriptions were recorded in the traditional pharmacopoeias. While herbal doctors deliver herbal medicines, the proportion of different herbs may vary according to the specific symptoms of each patient or according to the particular prescriptions. Therefore, the traditional Chinese herbal medicines could be very specific to a person or be of fixed composition. The ways to take the Chinese herbal medicine include decocting medicinal herbs, pounding the herbs into a powder and kneading the powders to make pills. The Chinese herbal medicine factories were only able to produce the herbal medicines according to the particular prescriptions, and the personal herbal medicines should be delivered by herbal doctors.
5. This article distinguishes herbal medicines from herbaceous medicines. While we use the term herbal medicines to refer to the traditional Chinese herbal medicines, we use the term herbaceous medicines to refer to the new medicines which are developed by herbs.
6. The Chinese universities included the National Defense Medical Centre. The Taiwanese universities included Taipei Medical University, Kaohsiung Medical University and China Medical University.
7. The majority of universities doing pharmaceutical research were the public universities. The scientists who worked in the public universities were considered to be civil servants who should obey the Civil Service Act and should not have any interactions with private companies. Therefore, interactions between scientists in the public universities and pharmaceutical companies were forbidden (LY, 2010).
8. Farmers' Insurance is a special kind of insurance particularly for farmers. The government would fund 60% of the insurance premium, and the farmers only need to pay for 40% of the insurance premium (CLA, 2010).

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