Analyzing the Brokerage Roles of Stakeholders in a Technological Network: A Study of GMO Plant Technologies

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Abstract--**Knowledge flows help to explain how technologies evolve from certain applications to other new directions. Flows in some technology show how stakeholders utilize the success of new inventions to improve human life, whereas some knowledge diffusion expresses that the dominance of technological development is embedded in a few stakeholders. We take genetic modified organism (GMO) technologies used in plants as the research context and discuss the development of biotechnology sectors in the past few decades. We also explore how industrial actors, governmental units, and universities have influenced the path of technological development. This study collects 4,365 patents, owned by 492 institutions, in USPTO (United States Patent and Trademark Office). We utilize patent citations to build the networks among technologies and among stakeholders. A main path analysis, i.e. the technological network, specifies the core developments in GMO technologies during this research time period. Through brokerage analysis of different stakeholders, some national governments show their importance on being a liaison among different stakeholders. United States industrial actors play a dominating role in the field, while European research agencies play a consultant role to facilitate knowledge flows among different nations.**

I. INTRODUCTION

Industrial growth and development always needs the support of technological progress. Relevant stakeholders in an industry, e.g. firms or research institutions, execute interactive learning mechanisms to improve their industrial technologies and to push the respective industry toward high value- added growth [28] In order to examine the interactions of technological knowledge flow, we explore in-depth how and whether specific stakeholders play a brokerage role that links together resources in different areas. This study aims to present the role of different stakeholders in the process of technological development. We take the technologies applied in genetically modified (GM) foods as our research context, because of their high growth in the past few decades. The diversification opportunities and challenges arising from the technology progress in this field offer a unique case to observe the technological trajectory and the knowledge interactions of relevant stakeholders.

Genetically modified food involves the insertion of a target gene that contains desirable traits, such as resistance to herbicides, pests, fungi, bacteria, viruses, insects, and disease as well as traits that help to produce high nutritional value and yield to the crops. This industry has emerged as a major force in global food production, resulting in hundreds of new GM plant varieties based on research and development (R&D) efforts. Despite the potential benefits of GM food, this scientific and technological innovation is surrounded by controversial issues pertaining to environmental health and safety, economics, and politics. To give a better understanding about this topic, the following sections are divided into a few parts and briefly introduce the development of GM food and the industry evolution in this field. We apply patent information to explore the technological trajectory in GM plant development and further explain the technological knowledge network. By exploring brokerage roles played by different stakeholders, we also target to clearly show the importance of specific players in this industrial field.

The purpose of this study is to give an idea about the development trajectory of the genetic engineering techniques involved in GM food and to discuss stakeholders' roles in the process of knowledge diffusion. First, by main path analysis, we shall find out the main technological trend in different stages. Second, we conduct an assignee network analysis to visualize the associated technology of agribusiness companies on a global level. In some developing countries, policy makers hope to gain global competiveness in agriculture development through this field. Our study allows us to observe the emergence of industry stakeholders, including seed, chemical, and pharmaceutical companies. We can also learn the core actors who own GMO technologies and play a critical role in diffusing relevant technologies.

This paper is organized into five sections. The next section discusses the background and growth of the GM food industry. The third section describes the relevant stakeholders and the brokerage concept that we use in this study. The fourth section focuses on the methodology and the boundary of research data. The fifth section explains the results and basic statistics, followed by the implications for this technological knowledge network. The last section presents our conclusion and limitations of this study.

II. DEVELOPMENT OF GENETICALLY MODIFIED FOOD

A. The growth of GM food

Genetically modified (GM) food emerged in the mid-1970s due to advances in cellular and molecular biology, sophisticated recombinant DNA techniques, and the huge amount of R&D capital invested by large corporations into this successful agricultural innovation system [30] According to the International Service for the Acquisition of Agri-Biotech Applications (ISAAA) report in 2012, global GM crops have increased 100-fold from 1.7 million hectares in 1996 to 170 million hectares in 2012, and it will continue to increase in the future (Fig. 1.). ISAAA summarized that 28 countries now plant GM crops, with 20 representing developing countries and 8 are industrial countries. Interestingly, 9 of the countries grow 97% of the world's total GM crops, while the other 19 countries each take up less than 1% of global hectares allocated to GM crops (Table 1). The total acreage of GM crops in developing countries is now larger than that in developed countries by 4%. The five leading biotechnology developing countries are China, India, Brazil, Argentina, and South Africa, which together plant more GM crops than industrial countries such as the U.S. and Canada [22] However, the Canadian Biotechnology Action Network (CBAN) argued that the increasing growth in developing countries is just accounted by the same countries (with the exception of Sudan and Cuba), dominated by Brazil and Argentina.

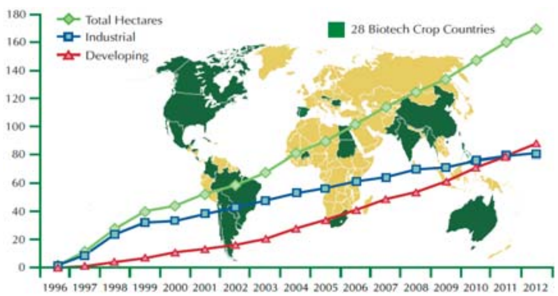

Fig. 1. Global area (million hectares) of GM crops from 1996-2012 [22]

Three categories of GM crops focus on improvements in agronomic traits: resistance to insects and herbicides, improvement of quality traits with higher nutrient contents of the GM food, and the production of substances for pharmaceutical and industrial purposes [32] Herbicide tolerant (HT) crops, resistant to glyphosate, represent the most common input traits for weed control [33] The most accepted insect resistance, which consists of the gene from a soil bacterium, is called *Bacillus thuringiensis* (BT), represents the only available commercialized insect-tolerant BT crop [33] Both of the HT and BT crops in the U.S. have seen an increasing amount of hectares since 1996 and have a high adoption rate by U.S. farmers, because they help to increase their net profits through potential cost savings ([8]; [35]). Up to now, there are 4 major types GM crops, including corn, soybean, canola, and cotton, with herbicide tolerant and/or insect tolerant traits. There are also GM crops with stacked traits that combine two or more genes of interest into a single plant. For instance, stacked genes have both herbicide tolerant and insect tolerant genes. Approximately 26% of the 170 million hectares of GM crops were stacked in 2012, implying an important trend in the next generation of GM crops [22] The GM traits discussed above are generally recognized as safe for human consumption, but the potential risks are controversial, such as environmental and health problems as well as economic issues between developed and developing countries.

TABLE1. PERCENTAGE OF GLOBAL GM CROP HECTARES (CBAN)

No	Country	Percent of global GM hectares
1	U.S.	40.80%
2	Brazil	21.50%
3	Argentina	14.00%
4	Canada	6.80%
5	India	6.30%
6	China	2.30%
7	Paraguay	2.00%
8	South Africa	1.70%
9	Pakistan	1.60%

*CBAN calculated the numbers in millions of hectares (actual data from ISAAA) as a percent of global GM hectares.

B. Research process in GM food technologies

The emergence of GM food technology has been known as a gene revolution that requires overall knowledge in advanced science and technology, resulting in huge R&D capital spent towards GM technology development [30] Based on the concept in [32], we observe that the process of developing a new variety of GM crop requires a complex sequence of technologies involved in patent applications. The process also requires several stages of confined field trial testing to evaluate the performance of GM crops before they are ready to be release into the environment [32] Therefore, the commercialization of GM crops is an extremely long-term research process that requires extensive regulatory procedures for product approval.

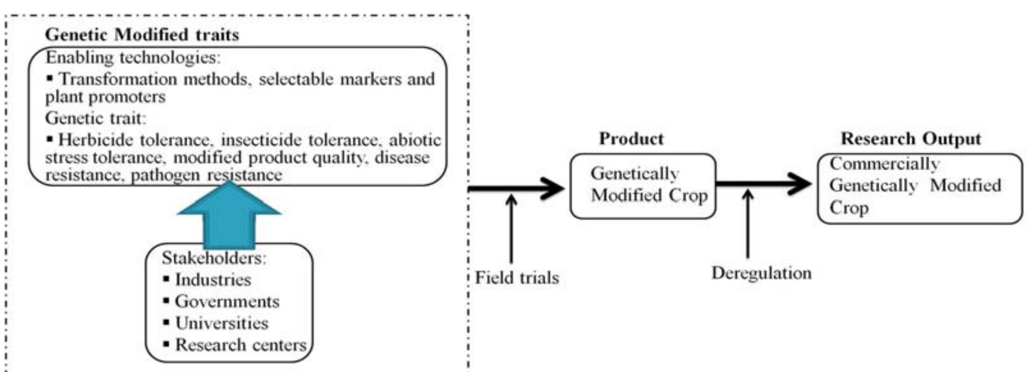

Fig. 2. GM food research process

It is important to find out how GM food technology diffuses during the whole evolution process and the reasons why it has been adopted at a much faster pace around the world. Studying the technological trajectory helps explain the development process of the technology as well as explore the phenomena of technology evolution. Past studies [29] indicated that the technological trajectory is like the path of developmental dynamics, or the direction of advance within a technology paradigm usually depends on the R&D strategies and the selected environment. The selected environment of a technology seems to create benefits for certain sectors from which stakeholders can utilize the resulting environmental advantages. Patent and citation data have been widely used as a useful approach to map the technological trajectories at the knowledge level ([16]; [21]). By investigating patent citation network data in this industry, we are able to trace the spread of the most important GM technologies among nations and to discover the role of the influential countries in such technology development.

Due to the time-consuming research process and extremely high R&D costs for the research inputs, the GM food industry may favor some private sectors, especially among industrial agriculture system countries [30] The study by [30] revealed that the reason behind those private sectors being predominantly led by multinational corporations is because they are able to increase shareholder investment values through other biotechnology firms. Thus, they are interested in carrying out intensive research to produce new transgenic crops. He explained that the technological trajectory in GM foods primarily depends on industrialized countries, because they have a strong influence on this intensive knowledge innovation process that results in tremendous implications on agriculture technology and food safety and security.

C. Intellectual property (IP) rights in Genetically Modified food

According to the study by [12], a GM seed or plant cultivar may consist of three different kinds of technological components that can be protected under IP (intellectual property) rights: (1) the germplasm of the plant variety, (2) the properties of genes that confer the new genetic trait, and (3) the fundamental tools including transformation methods, genetic markers, and promoters. The protection of IP rights has become a huge commercial incentive for multinational enterprises to move toward innovation activities. However, current IP rights are usually possessed by large private multinational companies of a few advanced countries, because of the high entry barriers of capital investment in GM technologies.

Privately owned agribusiness firms hold the overwhelming majority of GM food technology patents in the U.S. The case study by [13] divided organization types into two categories: public (academic or government organization) and private (commercial firm or individual inventor) sectors. The study presented that 74% of U.S. patents granted from 1981 to 2001 are from the private sector versus 24% from the public sector. The leading firms in the private sector, such as Monsanto, DuPont, Dow, Bayer and Syngenta, hold about 45% of all U.S. patents, which is nearly half of the total. Interestingly, among public sector organizations, no organization holds more than 2% of U.S. patents, including large public institutions such as University of California with 1.7% and U.S. Department of Agriculture [37] with 1.2%.

The GM food technology field has a significant entry barrier to any single institution to apply for new transgenic crops, because the IP rights of GM food technologies are held by several public and private sector owners. A typical example is GoldenRice (pro-vitamin A rice), which has more than 70 patents and patent applications issued in or applied for different institutional sectors, including patents on commercially accessed research tools ([31]; [25] It creates significant problems for farmers especially in developing countries to the adoption of GoldenRice in order to obtain the gene constructs and transgenic traits. These patents and licenses belong not only to Syngenta, but also to Bayer, Monsanto, Orynova, and Zeneca Mogen, with these companies eventually providing access to the required technologies with the right to sublicense in developing countries free of charge for humanitarian purposes [25] To observe how critical knowledge is diffused, we have to further explore the interactions among all different stakeholders in this field.

III. STAKEHOLDERS IN THE GM FOOD INDUSTRY

A. Industry evolution of Genetically Modified food

The success of GM food technology has resulted from a shift in agriculture innovation to market driven innovation. Research competency and financial strength along with intellectual property (IP) assets play crucial roles for the majority of R&D output measures [14] An industry's evolution can be quantified by measuring how the number of firms changes over time, while R&D activity can be measured by the total number of patents granted [32] The study of [19] showed that the tremendous consolidation of the global seed industry has happened since the commercialization of full patent protected transgenic seeds during the 1990s. Up until now, the industrial sectors involved in GM foods are mainly international agri-conglomerates that are made up through the integration of chemical or pharmaceutical, seed, and biotechnology companies that control the global GM seed industry [17]

The large percentage of leading firms that hold GM food patents usually acquired numerous smaller companies and merged with large competitors since the mid-1990s. The profound change in the GM food industry is that it is seen as no longer just being a "gene provider", but rather it has become a new sector of agribusiness carried out through many partnerships and mergers and acquisitions (M&As) [23] These structural changes allow mega firms to combine capabilities in different areas of GM food technology, such as biotechnology, agrochemicals, and seeds, thus corresponding to a consolidation process. Howard [19] pointed out that global transgenic seed companies are dominated between the Big Six corporations (Monsanto, DuPont, Syngenta, Bayer, Dow, and BASF), which share transgenic traits by implementing cross-licensing agreements. They are mostly from developed countries, e.g. the U.S., UK, and Germany.

A past study [9] examined the reasons behind the structural changes that have occurred in the GM food industry. A substantial number of M&A activities involving horizontal and vertical integrations has been frequently undertaken by seed and chemical industries. Horizontal M&A that has primarily occurred in seed and chemical industries can be explained by R&D costs, economies of scale and scope created by IP rights, and regulatory costs [9] Horizontal integration can increase concentration and market power by lowering sunk costs in order to achieve a dominant role in the market. Vertical integration encompasses combining seed, chemical, and biotechnology activities within the same firm that can be linked to product complementarities and difficulty to have access to IP rights [9] A single firm that produces both transgenic seed and chemical products can be more profitable and incur a tradeoff for market loss than separate firms that manufacture these same products. Furthermore, a single firm can maintain and strengthen the key traits of a certain type of transgenic crop and be able to obtain more economic profits. Overall, M&A activities have been effectively implemented by several major multinational companies to overcome the IP constraints that may result in barriers to the development and introduction of GM products [40]

Due to IP protection, the development of advanced technology depends much more on the research-intensive private sector rather than universities and other public sector institutions [6] Therefore, an organization, Public Intellectual Property Resource for Agriculture (PIPRA), in the U.S. provides collaborative IP management solutions to both public and private sectors ([6]; [11]). This type of institution plays a key role in ensuring widespread access to GM food technologies and determines the applicability and availability of technologies from both public and private sectors. Another private and non-profit institute located in Australia, called CAMBRIA, helps to develop and deliver new agriculture biotechnology through licensing to companies and transfers to national programs and universities in developing countries [6]

B. Brokerages facilitate knowledge flows in the industry

GM food technology has been considered as an example of food and agriculture innovation to solve the problem of global hunger. The study of [24] indicated that industrialized countries have experienced huge structural changes in agriculture and the privatization of public agriculture research into private systems in order to support knowledge infrastructure under this new innovation system. The result is the emergence of specialized intermediary organizations with regard to agriculture sectors [24] As the GM food industry has been monopolized by a few mega firms, it is well worth it to investigate their intermediate positions as well as their impacts upon others.

Along with the high growth in the GM food industry, relevant players around the world have invested a large amount of money into R&D efforts and relevant technology developments. Although up to now the U.S. is still the most influential country with the largest research capacity from mega firms to develop and disseminate GM food technology, several European firms and research institutions also possess related technologies. Numerous collaborative R&D projects have also been carried out between developed and developing countries. In addition, according to the study of GM technology patents by [13], the U.S. has invested heavily in the GM food technologies. When discussing the development of GM technologies, we have further to explore the knowledge flows across borders and across different types of institutional backgrounds from the view of network brokerages ([18]; [21]). Cross-national and cross-institutional knowledge flows also help to identify the different technological positions played by different stakeholders in this field.

There is a variety of intermediaries that play some kind of agency or broker role in order to facilitate the flow of knowledge and diffusion process [10] The ability of broker interactions to interface between different groups across structural gaps helps control resource flows and achieve higher rates of return during exchange relations ([15]; [36] Brokerage roles include five types. First, *coordinator* occurs when all three individuals belong to the same affiliated subgroup or class. A broker enhances the interaction between members of the group. Second, *representative* helps to diffuse knowledge of one's own group to another group. Third, *gatekeeper* is responsible for absorbing knowledge from a group and passing it to the group that it belongs to. Fourth, *consultant* bridges the resources of two members in the same group, but the consultant does not belong to this group. The fifth role is *liaison*. It occurs when all three individuals involved are affiliated with different subgroups, which enhances as an outsider interaction between different groups.

Because of these different brokerage roles, knowledge flow can be facilitated among all different stakeholders. When stakeholders belong to different subgroups, e.g. nations or institutions, a brokerage analysis allows us to understand how the knowledge diffuses in this industry. Therefore, our study conducts such an analysis to discover those actors and their influential roles among different groups.

IV. METHODOLOGIES

A. Databases from United States Patent Trademark Office

In this study we use patent data from United States Patent Trademark Office (USPTO). According to [13], GM food technology is separated into two categories: the fundamental 'enabling' technologies that represent the research tools required to create transgenic crops and the 'trait' technologies that provide the genetic basis for new functionalities. Therefore, we construct two sets of keywords to fit into these categories. For the 'enabling' technology, the queries include three major technologies: transformation methods (*Agrobacterium* mediated gene transfer and biolistic mediated gene transfer), selectable markers (Ti plasmid and CaMV 35s plasmid), and plant promoters (constitutive promoter and genetic regulatory system). For the keywords of 'trait' technologies, there are six different technology clusters of commercial genetic modified traits: herbicide tolerance, virus resistance, crop product quality trait, pathogen resistance, disease resistance, and bacillus toxin. We also include during the database search 42 names of varieties of transgenic crops: alfalfa, anthirrhinum, apple, arabidopsis, banana, barley, brassica, cassava, corn, cotton, cucumis, glycine max, gossypium, fescue, legume, lettuce, maize, medicago, millet, nicotiana, oat, oil-seed rape, pea, pepper, petunia, poplar, potato, prunus, pulse, rice, rye, sorghum, soybean, solanum, strawberry, sugar beet, sugarcane, sunflower, tobacco, tomato, wheat, and zea [38] All the keywords were combined using the BOOLEAN connectors of OR or AND. Finally, based on the study [39], the screening of non- relevant records can be excluded by using ANDNOT. These non- relevant records are categorized into four sections: (1) transgenic organisms (*Agrobacteria*, fungior viruses) interacting with plants, (2) the use of the terms "transformation", "regeneration", "plant", "GM", and "chimeric gene" for a purpose other than plant genetic engineering, (3) *In vitro* cell and tissue culture studies only mentioning their potential interest for future plant transformation, and (4) the addition of unspecific database-generated keywords. We obtain a clean database after excluding non-relevant records.

B. Main path analysis

Main path analysis uses citation information in bibliographic publications from either academic papers or patents to trace the main idea flow as well as to highlight the central documents for the development of a specific discipline [5] Identifying the highest value of a connectivity link of citations in a network, which consists of most of the knowledge flows passing through it, is the first step in finding the main path. Patent citation can be used as an indicator of technology spillovers, while patent statistics can be used to analyze the diffusion of technology from one country to another ([1]; [4]). In a citation network, a 'source' is a node that is cited without citing other nodes, while a 'sink' is a node that cites other nodes, but itself is not cited.

During the citation analysis, there are three variations to conduct the count: search path link count (SPLC), search path nodes pair (SPNP), and search path count (SPC) ([2]; [20]). We use SPC count throughout our study, and Figure 3 shows a demonstration of SPC count in a simple citation network. From the definition of source and sink, there are two sources, A and B, while there are three sinks, J, K, and H. There are many alternative paths to go from sources to sinks. In order to calculate the SPC value, we need to multiply the value of every source that is possible to reach the sink. For example, if we need to calculate the SPC value of link CE, there are six possible paths to pass through, which are from source A (A-C-E-F-I-K, A-C-E-F-I-J, and A-C-E-F-G-H) and from source B (B-C-E-F-I-K, B-C-E-F-I-J, and B-C-E-F-G-H). Therefore, link CE has SPC value equal to source A, and B is multiplied by sinks H, J, and K, so we see 2 being multiplied by 3, giving 6 as a result.

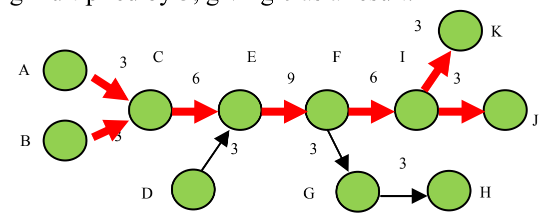

Fig. 3. SPC example

In our study, we analyze the global main path which measures the overall importance in knowledge flow. The global main path is the path which we select the largest SPC value of each path that has the highest traversal weight from the source to the sink, which gives the whole Global 1 main path. For example, if we select Global 10 main path, meaning that the main path consist of ten different paths and each of them have the overall largest SPC value.

C. Assignee network and brokerage analysis

Based on the theory by [10], a partition of actors can be specified into five different brokerage positions by their given scores, using UCINET which is social network analysis software. There are 492 patent assignees (actors) in our study, and they are partitioned into five different brokerage roles according to two different attributes: countries and institutions. UCINET software calculates the measures for each node in the network for each type of brokerage role and also provides an output table with each of the five brokerage scores together with the total score of all the roles. Therefore, every assignee in the patent citation network plays a specific brokerage role according to the attribute given.

V. RESULTS

There are a total of 4,365 patents collected from USPTO covering the period 1980 to 2013. Because we focus on the technologies relevant to main path development, the patents that have no citations and are not citing any other patents or papers in the raw dataset were removed in assignee network analysis. The final dataset includes 3,710 patents. As some of the patents consists of multiple inventors so we put them into individual patent with every different inventor involved so that it is easy to carry out the description statistic analysis. These patents are owned by 492 assignees, from which we can further explore the importance of different stakeholders in this industry.

A. Distribution of patents

According to the statistics of patent outputs, U.S., DE, and JP are the top three countries that produce the most patents in GMO technologies. The top 10 countries make up more than 92% of the total granted patents (Table 2). Among these top patent output countries, the U.S. owns around 60% of GMO patents in the world. From the assignee numbers that own these patents, the U.S. is still the leader with more than two hundreds firms. Germany, Japan, United Kingdom, Canada, and France also have more than twenty institutions in this field. Among assignee numbers, Japan is in second place with a high capability at developing GM technologies. Although Japan has invested heavily in this technology, the support and acceptance of GM food by either stakeholders or consumers in Japan are low due to concerns about the risk assessment of GM food.

B. The main path analysis

Through main path analysis, Figure 4 shows the development of GM food technologies. The arrows point in the direction of knowledge flow, and the thickness of line reflects the SPC value. The thicker the line is, the more important the route is that shows the direction that critical GM technological knowledge flows . Each node represents a patent along with its patent number in USPTO and the years when the patent was applied and then approved (e.g. US4407956_1981_1983). Based on the patents displayed on the main path, we identify five different categories. Starting from the source of the main path, it displays a continuous and stable development of technology without having other branches until it comes to patent US6013863. It then divides the major path into two different domains, and each of the domains develops its own technology area.

The first technology domain discusses the process of the vector expression system that plays a crucial part in activating the foreign genes that have been transformed into the target GM plant. The important source (green dot) discusses CaMV 35S promoter, which relates to the transcriptional regulatory mechanism. It is widely used in all current transgenic crops that are released commercially or undergoing field trials. The next technology domain discusses the creation of a chimeric gene involved in recombinant DNA integration that is capable of being expressed in plant cells for creating herbicide tolerant plants and antibiotic tolerant plants. The first and two technology domains represent the enabling technology in GM food.

The rest of the three technology domains are related to the traits technology that incorporated in the crops. Next is the invention of transgenic Zea mays (referred to as maize or corn) that is resistant to the herbicide glyphosate via a particle bombardment technique. And then, it is followed by two distinct technology domains that discuss two common GM traits: abiotic stress tolerance and modified product quality.

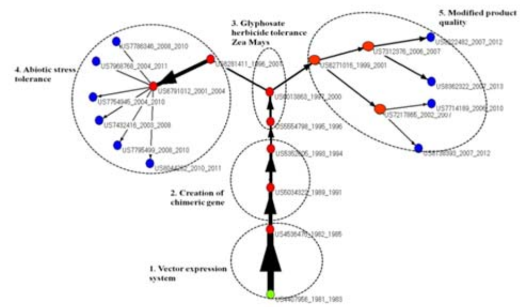

Fig. 4. Global main path of GM food technology

We identify several stages from main path analysis (Table 3). Monsanto and University of California are the active assignees involved in the earliest stage of GM food technology. University of California represents the assignee of the source that focuses on CaMV 35S promoter. It has been widely used for the construction of herbicide and disease resistant transgenic plants due to its stable properties that are not influenced by environmental conditions or tissue types [34] On the main path analysis, Monsanto patents are related to the expression of triggering chimeric genes that have been transformed in a GM plant. Monsanto is also active in the development of GM plants with modified product quality during the later stage of GM food technology evolution.

TABLE 2. DISTRIBUTION OF PATENTS AND ASSIGNEES BY COUNTRIES

NA	Patent number	%	Assignee number	%
US	2444	59.36%	213	43.29%
DE	346	8.40%	21	4.27%
JP	195	4.74%	43	8..74%
UK	166	4.03%	27	5.49%
CA	136	3.30%	20	4.07%
CH	126	3.06%	7	1.42%
FR	104	2.53%	24	4.88%
BE	94	2.28%	6	1.22%
AU	93	2.26%	18	3.66%
NL	82	1.99%	18	3.66%
KR	55	1.34%	14	2.85%
Others	276	6.2%	81	26.81%
Total	4117	100%	492	100%

Note: US: United States; DE: Germany; JP: Japan; UK: United Kingdom; CA: Canada; CH: Switzerland; FR: France; BE: Belgium; AU: Australia; NL: Netherlands; KR: South Korea.

TABLE 3. SUMMARY OF PATENT DESCRIPTIONS ON GLOBAL MAIN PATH

No	Time	Technology domain	Field of invention	Key assignees
1	1983-1985	Vector expression system	● Modifying *Agrobacterium tumefaciens* and CaMV 35S gene in a vector expression system while maintaining infectivity, movement, and the ability for high multiplication.	University of California, Monsanto
2	1991-1994	Creation of chimeric gene	● Creation of chimeric genes that contain promoter region, partial coding, or structural sequence derived from antibiotic resistance region and 3' non-translated region.	Monsanto
3	1996-2000	Glyphosate herbicide tolerance Zea mays	● A process for producing fertile transformed plants of graminaceous plants other than Zea mays based upon microprojectile bombardment, which have not been reliably transformed by traditional methods, e.g. electroporation, *Afrobacterium*, injection, and previous bioelectric ballistic techniques.	Dekalb Genetics
4	2001-2011	Abiotic stress tolerance	● Generation of GM plants with tolerance of water, salt, and drought tolerance phenotypes.	Dekalb Genetics, Rutgers University, Agrigenetics, Dow, Agroscience and Agrinomics
5	2001-2013	Modified product quality	● Generation of GM plants with modified amino acid, modified oil/fatty acid, lignin, and modified starch/carbohydrate.	Monsanto, Renessen, Ceres

The next stage of GM development is responsible by Dekalb Genetics which focuses on glyphosate resistant (GR) in which the DNA has been altered to withstand herbicide glyphosate in maize and corn. Dekalb is best known for its leading role in the production of maize and corn seed, but was purchased by Monsanto in 1998. According to the GM Approval Database published by ISAAA, GR has been widely adopted in a variety of crops, such as soybean, maize, cotton, canola, sugar beet, wheat, potato, alfalfa, and creeping bentgrass. Approximately 80% of the total area for global GM crops is devoted to GR crops, which are also called Roundup Ready crops, which have brought economic advantage to farmers due to simple and superior weed management [7] Apart from the invention of glyphosate resistant (GR) transgenic corn plants, Dekalbs also has tried to alter the glycine-betaine content of a plant that plays an important role in improving osmotic adjustment during salinity stress.

After the development of the glyphosate herbicide tolerance trait, the main path shifts to the development of GM traits of abiotic stress tolerance and modified product quality. Drought stress has been the most significant environmental stress factor in agriculture worldwide. Therefore, transgenic plants with improved drought tolerance can help to cope with a drought event that tends to occur every year in certain countries. There are several assignees responsible to these patents. Moreover, transgenic plants with modified product quality are involved in tryptophan overproduction and altering the nutritional contents, such as amino acids, fatty acids, oil, and carbohydrates, of transgenic plants. A transgenic plant with altered oil levels could be a source for the discovery of new medicinal value for drug development, such as plant-made pharmaceuticals or plant-made vaccines [26] The transgenic plant with altered lignin levels is related to the composition of the cell wall structure that enhances forage digestibility and pulping efficiency [27]

C. Assignees' network analysis and their brokerage roles

1) Assignees' network analysis among actors

We use the assignees network in Fig. 5 to show the knowledge flows among different actors. To show the obvious linkages, we take a simplified network, which only includes those citations of more than 10 times, to observe the interactions among stakeholders. Arrows note the pattern of knowledge flows. A thicker strength of ties represents strong connections of knowledge flows among nations.

In the central area of the network, we find that most of the institutions belong in the U.S. Monsanto, Dekalb, Pioneer, DuPont, and Verdia have high centrality in the network and also strong ties between each other. Connections between biotechnology firms and the seed industry are strong. A series of mergers and acquisitions and alliances between them took place following the commercialization of GM seeds in 1996.

As shown by [19], many large firms tend to take an M&A strategy to diversify their business and strengthen technological capabilities. Seed companies such as Dekalb and Pioneer have been acquired by large agri-biotech companies. Monsanto acquired Dekalb in 1998, while Dupont took over Pioneer in 1999. Verdia is an expert in the molecular breeding area for agricultural applications and was acquired by DuPont in 2004. In the future, Monsanto and DuPont plan to continue to acquire or create partnerships with other independent seed companies that still exist in order to control their food systems. The citation network seems to express their intensive interactions and cooperation in the real world and also implies that the process of technological learning might generate some drivers for different actors to cooperate in the real world.

In the network we also observe that several universities play a mediator role among stakeholders. For example, Cornell University absorbs knowledge from other universities or industrial actors in the central area and diffuses knowledge to institutions in the peripheral area of the network. University of Washington and Colorado State University also have intensive linkages with specific industrial companies. This explains that technology flows also need the participation of universities, even though most actors in the central area of the network are industrial actors.

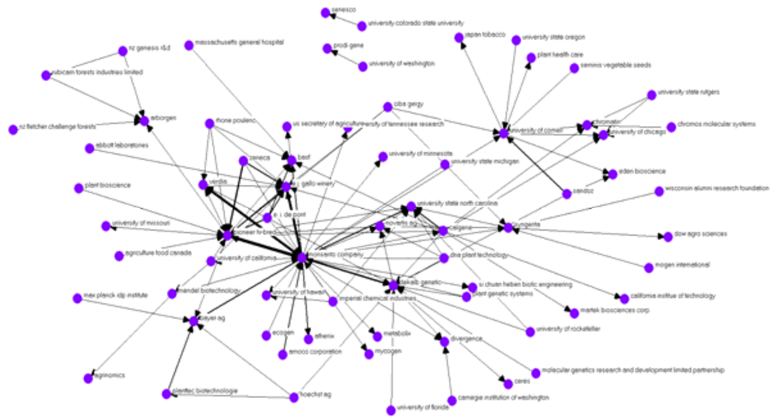

Fig. 5. Assignees' network analysis

2) Cross-nation brokerage

The assignees that have highest value among each brokerage role are mostly from the U.S. (Table 4). Institutions there are either industrial firms or universities and tend to have a higher value in their particular type of brokerage role, such as coordinator, gatekeeper and representative. For instance, the top five brokerage positions of coordinator, gatekeeper, and representative are all in the U.S. In addition, the top 10 representatives are all from American firms. This result shows that U.S. stakeholders have made relatively higher efforts on knowledge interactions within the U.S., and the reason might be because the GM food industry has grown so rapidly in the past few years. Because of the high resource commitment within the U.S., this country plays an influential role on the direction of GM food technologies.

For the consultant role, apart from Pioneer Hi-bred, the others are from Canada, Switzerland, and Denmark. In other words, the consultant role is the least role played by American institutions. This seems to express that knowledge belonging to American firms tends to become the bridge for the actors in a specific country. Another similar phenomenon happens in the position of liaison is involve in some European countries and Canada, which is responsible for building a bridge of technology transfer among more than three countries. Overall speaking, U.S. institutions especially the largest agri-biotech company, Monsanto is still the world leaders of the GM food industry, having sophisticated network connections to assess and explore any key strategic technologies among nations. University in the U.S. also play a critical role to mediate resources across nations, including California University and Cornell University. Canadian National Research Council and German Max Planck Institute are both research institutions that link their resources among different nations.

3) Cross-institution brokerage

We also classify all assignees on the basis of their institutional types, i.e. research institution, university, industry, and government, to observe those actors playing different brokerage roles among these different institutions. According to the institutional types of assignees, industrial actors occupy the majority among all assignees (Table 5). More than half of all assignees are industrial actors, and about one-fourth of assignees belong to the university system. Among all assignees, research institutions are about 15%, whereas governmental units are only 2%. However, both of their institutional roles in facilitating knowledge flows are still important in different types of brokerages that can bridge resources among stakeholders.

TABLE 4. THE TOP TEN HIGHEST NUMBER OF EACH BROKERAGE ROLE AMONG NATIONS

COORDINATOR	NO.	GATEKEEPER	NO.	REPRESENTATIVE	NO.	CONSULTANT	NO.	LIASON	NO.
Pioneer Hi-bred	231	Pioneer Hi-bred	286	Monsanto	291	Ciba Geigy[2]	66	Pioneer Hi-bred	262
Monsanto	216	Monsanto	203	Pioneer Hi-bred	221	CA National Research Council[1]	61	Monsanto	247
California Uni	169	California Uni	141	California Uni	183	Syngenta[2]	51	Syngenta[2]	142
Cornell Uni	154	Cornell Uni	89	Cornell Uni	105	Novartis Ag[2]	47	California Uni	139
Calgene	98	Calgene	71	Calgene	92	Agriculture Food[1]	33	CA national research council[1]	81
State Michigan Uni	86	Basf[3]	51	State Michigan Uni	52	Bayer Ag	28	Bayer Ag	79
Washington Uni	51	State Rutgers Uni	46	Washington Uni	47	Monsanto	23	Calgene	62
Florida Uni	36	Ministry Agriculture[5]	45	Kentucky Uni	35	Max Planck Institute[3]	20	Cornell Uni	62
Kentucky Uni	35	Kentucky Uni	40	Purdue Research	33	Pioneer Hi-bred	17	Novartis Ag[2]	61
US Secretary Agriculture	33	State Michigan Uni	34	Cargill	32	Plant Genetic Systems[4]	17	Plant Genetic Systems[4]	60

Note: 1: CA; 2: CH; 3: DE; 4: BE; 5: JP; the rest without putting are all US.

TABLE 5. THE TOP TEN HIGHEST NUMBER OF EACH BROKERAGE ROLE AMONG INSTITUTIONS

COORDINATOR	NO.	GATEKEEPER	NO.	REPRESENTATIVE	NO.	CONSULTANT	NO.	LIAISON	NO.
Monsanto	286	Monsanto	311	Pioneer Hi-bred	252	Pioneer Hi-bred	124	Pioneer Hi-bred	148
Pioneer Hi-bred	230	Pioneer Hi-bred	263	Monsanto	186	California Uni[1]	121	Monsanto	111
California Uni[1]	116	California Uni [1]	137	California Uni[1]	176	Monsanto	86	National Research Council[3]	105
Calgene	88	Cornell Uni[1]	107	Cornell Uni [1]	104	State Michigan Uni [1]	82	California Uni [1]	91
Cornell Uni[1]	83	Calgene	93	Calgene	77	Cornell Uni[1]	61	Agriculture Food Canada[2]	62
Ciba Geigy	50	Kentucky Uni [1]	78	Ciba Geigy	44	State Rutgers Uni[1]	45	Cornell Uni [1]	57
Bayer Ag	46	Syngenta	61	Cargill	43	National Research Council[3]	42	Syngenta	57
Basf	45	Bayer Ag	50	State Michigan Uni [1]	42	Salk Institute	41	US Secretary Agriculture [2]	54
Plant Genetic Systems	30	Basf	38	Washington Uni[1]	33	Purdue Research[3]	40	JP Agriculture Ministry [2]	48
Washington Uni [1]	27	State Michigan Uni [1]	33	State Rutgers Uni[1]	30	Calgene	36	Purdue Research [3]	46

Note: 1: university; 2: government; 3: research center; the rest are all industry.

The industrial companies are dominated by Monsanto, Pioneer, and DuPont, while the universities are dominated by University of California, Cornell University, and Michigan State University. The result also shows that industrial companies are the majority in all brokerage positions, especially that of coordinator (Table 5). Only a few universities, e.g. University of California and Cornell University, are listed in the top 10. For the part of gatekeeper and representative, universities show their importance in absorbing knowledge from other universities or diffusing knowledge to external institutions. Universities, as important as industrial actors are, play a representative role of sharing academic resources with other external actors. In addition, compared to other types of brokerages, universities and research institutions are becoming more important than other industrial companies. This implies that some industrial actors may need universities' mediation to link up with some other industrial actors and exchange resources. The role of liaison helps link resources across three types of institutions. Aside from the mega firms in the GM food industry, some governmental institutions and universities may also be capable of taking on the role of liaison and stimulate knowledge transfer among stakeholders in different areas.

D. Facing new challenges in GM food technological development

This study explores the technological development applied in GM foods and identifies the development of critical knowledge for this industry's growth. However, whether GM crops should continue to be planted all over the world still faces many different arguments. Scientists still are unable to clearly evaluate the risk of consuming GM food as well as the environmental issues from a long-run perspective, because the history of GM crop technologies has just emerged for about three decades. The empirical evidence shows that high technological capabilities are owned by industrial actors and universities in the U.S. Although one of the reasons might be that the extracted dataset is based on USPTO, we cannot deny that all cross-national coordinators are all from the U.S. The result seems to explain that industrial technologies are dominated by a few large firms and research universities in the U.S. In addition, the representatives and gatekeepers are also mostly from the U.S. Stakeholders in the U.S. also possess most of the critical knowledge within their domestic area. In other words, most other foreign stakeholders may be facing difficulties in identifying the right direction for GM technologies and have been misled to execute inappropriate innovations.

Our study expresses that the U.S. has established a very strong GM knowledge base in industrial fields as well as in research universities. Some European institutions also possess critical patents, but their brokering behaviors (e.g. as a consultant) seem to not build upon the knowledge base in their home country, but instead on facilitating interactions with other countries. Compared to other countries, U.S. actors show their high resource commitment in GM food technologies, but if we observe the high growth of GM crops shown in the ISAAA report, then the higher growth appears mostly in developing countries. Developing countries seem to experience irresistible forces, as GM technologies can bring advantages to their domestic agricultural productions. We cannot concretely argue that GM food technologies are risky for human beings, but all the relevant stakeholders have to make efforts to diminish dominance by the U.S. and develop a balance of knowledge that is possessed by different national stakeholders and institutional stakeholders.

VI. CONCLUSIONS

In this study we apply main path analysis and brokerage analysis to explore the development of GM food technologies and the importance of different stakeholders in this field. The evolution of GM technology is moving from herbicide resistant and drought resistant GM crops to the production of pharmaceutical GM crops with altered oil levels and nutritional value, presenting technological breakthroughs and new opportunities for GM agricultural sectors. The U.S. has taken the world's leading position in the adoption of this technology, even though the majority of GM crops are planted in other developing countries. The network expresses the interactions among different stakeholders from different countries and different institutions. Monsanto, one of the mega firms, has established a strong network position that connects to various nations and diversified institutional actors. American firms perform relatively better than other countries in coordinating resources within the U.S. due to its high centrality in the network. Several leading American firms, e.g. Monsanto and Pioneer Hi-bred, locate in the central area of network and have an influential role on the direction of the technology development process.

The brokerage analysis also helps to identify the role of research institutions and universities during the process of knowledge diffusion. Almost half of the assignees belong to the industrial field, but the linkages among university and industrial actors still require contribution from governmental units. After observing the cross-institutional brokerages, governments seem to show a higher importance in linking resources among different institutional backgrounds. If the knowledge flows imply real actions among stakeholders, then the liaison's function has to rely on governmental support and funding. If governmental units support the development of GM food technology, then stakeholders of different institutional types will be able to build up their cooperative relationships. Some universities have made contributions to bridge their knowledge between other universities and external actors, as evidenced by academic research putting a lot of effort on the development of GM food technologies. From the interactions of a cross-institutional network, the development of GM food technologies within the sector innovation system relies on various collaborative efforts by all three types of stakeholders. However, the American actors still play a dominant role on the development of GM food technologies. To reduce the uncertain risks of using their technologies, non-U.S. actors should rely more on their interactive relationships with stakeholders in different countries.

There are several limitations inherent in this study. First, we only use the headquarters location as the country for all multinational corporations, which results in the exclusion of citation relationships of other countries in the assignee network. Second, the technological trajectory is built on the basis of the database of USPTO, which approves more GM technologies than EPO (European Patent Office). Most policy makers in European countries take the GMO-skepticism approach to regulation due to uncertainty about the risks posed by GM foods. Therefore, using just USPTO's patent database would eventually generate more U.S.-based stakeholders, resulting in a bias during our study. In addition, we only apply patent citations to measure the technology flows and patent statistics to analyze the brokerage role of different stakeholders. Apart from just narrowing down the patent database, there might be some missing paths ignored in this dataset. To make this concept more widely discussed, we suggest that the arguments existing in academic studies should also be taken into account in another main path study. The issues about consumers' health and environmental safety concerns are surrounded by different controversies. To explore more aspects in the development of GM food technologies, future studies can also integrate information from other scientific databases (e.g. WOS) so that some new and different insights of the development trajectories in the GM food industry can also be presented. Lastly, any further study will have to carry out a regression analysis to explore whether and how different brokerage roles significantly affect the process of knowledge flow in GMO plant technologies.

REFERENCES

[1] Basberg, B. L.; "Patents and the measurement of technological change: a survey of the literature," *Research policy*, vol. 16, pp. 131-141, 1987.

[2] Batagelj, V.; "Efficient algorithms for citation network analysis," University of Ljubljana, Department of Mathematics, *arXiv preprint cs/0309023*, 2003.

[3] Burt, R. S.; "Toward a structural theory of action: network models of social Structure, Perception, and Action," 1982.

[4] Caballero, R. J., and Jaffe, A. B., "How high are the giants' shoulders: An empirical assessment of knowledge spillovers and creative destruction in a model of economic growth," *In NBER Macroeconomics Annual 1993*, MIT press, vol. 8, pp. 15-86, 1993.

[5] de Nooy, W., Mrvar, A., and Batagelj, V., "Exploratory social network analysis with Pajek," *Cambridge University Press*, 2005.

[6] Delmer, D. P., Nottenburg, C., Graff, G. D., and Bennett, A. B., "Intellectual property resources for international development in agriculture," *Plant Physiology*, vol. 133, pp. 1666-1670, 2003.

[7] Duke, S. O., and Powles, S. B., "Glyphosate-resistant crops and weeds: now and in the future," *AgBioForum*, vol. 12, pp. 346-357, 2009.

[8] Fernandez-Cornejo, J. and McBride, W.D., "Adoption of bioengineered crops," *Agricultural Economic Report*, No. 810.

[9] Fulton, M., and Giannakas, K., "Agricultural biotechnology and industry structure," *AgBioForum*, Vol. 4, pp. 137-151, 2002.

[10] Gould, R. V., and Fernandez, R. M., "Structures of mediation: A formal approach to brokerage in transaction networks," *Sociological methodology*, pp. 89-126, 1989.

[11] Graff, G., Wright, B., Bennett, A., and Zilberman, D., "Access to intellectual property is a major obstacle to developing transgenic horticultural crops," *California Agriculture*, vol. 58, pp. 120-126, 2004.

[12] Graff, G., and Zilberman, D., "An intellectual property clearinghouse for agricultural biotechnology," *Nature Biotechnology*, vol. 19, pp. 1179-1180, 2001.

[13] Graff, G. D., Cullen, S. E., Bradford, K. J., Zilberman, D., and Bennett, A. B., "The public-private structure of intellectual property ownership in agricultural biotechnology," *Nature biotechnology*, vol. 21, pp. 989-995, 2003.

[14] Graff, G. D., and Newcomb, J., "Agricultural biotechnology at the crossroads," *BioEconomic Research Associates*, pp. 23-25, 2003.

[15] Granovetter, M. S.; "The strength of weak ties," *American journal of sociology,* pp. 1360-1380, 1973.

[16] Griliches, Z.; "The search for R&D spillovers, " *National Bureau of Economic Research*, 1992.

[17] Hayenga, M.; "Structural change in the biotech seed and chemical industrial complex," *AgBioForum*, Vol. 1, pp. 43-55, 1999.

[18] Ho, M. H. C., and Verspagen, B., "The role of national border and regions in knowledge flows. In N. Lorenz & A. Lundvall (Eds.), How

Europe's Economies Learn," *UK: Oxford University Pres*., 2006.

[19] Howard, P. H.; "Visualizing consolidation in the global seed industry: 1996–2008," *Sustainability*, vol. 1, pp. 1266-1287, 2009.

[20] Hummon, N. P., and Dereian, P., "Connectivity in a citation network: The development of DNA theory," *Social Networks*, vol. 11, pp. 39-63, 1989.

[21] Jaffe, A. B., Trajtenberg, M., and Henderson, R., "Geographic localization of knowledge spillovers as evidenced by patent citations," *the Quarterly journal of Economics*, vol. 108, pp. 577-598, 1993.

[22] James, C.; "Global Status of Commercialized Biotech/GM Crops: 2011," ISAAA Brief 43, *ISAAA Briefs. Ithaca, New York: International Service for the Acquisition of Agri-biotech Applications (ISAAA),* Retrieved November, 2012.

[23] Joly, P.-B., and Lemarié, S., "Industry Consolidation, Public Attitude, and the Future of Plant Biotechnology in Europe," *AgBioForum*, vol. 1(2), pp. 85-90, 1999.

[24] Klerkx, L., and Leeuwis, C., "Matching demand and supply in the agricultural knowledge infrastructure: Experiences with innovation intermediaries," *Food Policy*, vol. 33, pp. 260-276, 2008.

[25] Kryder, R. David, Stanley P. Kowalski, and Anatole F. Krattiger., "The Intellectual and Technical Property Components of pro-Vitamin A Rice (GoldenRiceTM): A Preliminary Freedom-To-Operate Review," ISAAA Briefs No. 20. *ISAAA: Ithaca, NY. 56p, 2000.*

[26] Kutchan, T.; "The Biotechnological exploitation of medicinal plants. In The role of natural products in drug discovery," *Springer Berlin Heidelberg*, vol. 32, pp. 269-285, 2000.

[27] Li, X., Weng, J. K., and Chapple, C., "Improvement of biomass through lignin modification," *The Plant Journal,* vol.54, pp. 569-581, 2008.

[28] Lundvall, B.-Å. (Ed.); "National Innovation Systems: Towards a Theory of Innovation and Interactive Learning," *London, Pinter Publishers*, 1992.

[29] Nelson, R. R., and Winter, S. G., "In search of useful theory of innovation," *Research policy*, vol. 6, pp. 36-76, 1977.

[30] Parayil, G.; "Mapping technological trajectories of the Green Revolution and the Gene Revolution from modernization to globalization," *Research Policy,* vol. 32, pp. 971-990, 2003.

[31] Potrykus, I.; "Golden rice and beyond." *Plant Physiology* vol. 125, pp. 1157-1161, 2001.

[32] Pray, C., Oehmke, J. F., and Naseem, A., "Innovation and dynamic efficiency in plant biotechnology: An introduction to the researchable issues," *AgBioForum*, Vol. 8, pp. 52-63, 2005.

[33] Qaim, M.; "The economics of genetically modified crops," *Annual Review of Resource Economics*, vol. 1, pp. 665-695, 2009.

[34] Smith, H. A., Swaney, S. L., Parks, T. D., Wernsman, E. A., and Dougherty, W. G., "Transgenic plant virus resistance mediated by untranslatable sense RNAs: expression, regulation, and fate of nonessential RNAs," *The Plant Cell Online*, vol. 6, pp. 1441-1453, 1994.

[35] Soule, M., Klotz-Ingram, C., Daberkow, S., and Goodhue, R., "Adoption of Bioengineered Crops," *Economic Research Service/USDA*, Agricultural Economic Report No. 810, 2002.

[36] Täube, V. G.; "Measuring the social capital of brokerage roles," *Connections* vol. 26, pp. 29-52, 2004.

[37] USDA; "Recent Trends in GE adoption," June Agriculture Survey, *U.S. Dept. of Agriculture, National Agriculture Statistics Service (NASS)*, Retrieved November, 2001.

[38] Vain, P.; "Global trends in plant transgenic science and technology (1973–2003)," *TRENDS in Biotechnology*, vol. 24, pp. 206-211, 2006.

[39] Vain, P.; "Trends in GM crop, food and feed safety literature," *Nature biotechnology,* vol. 25, pp. 624-626, 2007.

[40] Van Wijk, J., Cohen, J., and Komen, J., "Intellectual property rights for agricul-tural biotechnology: Options and implications for developing countries. A biotechnology research management study," *ISNAR Research Report* , 1993.