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The Sectoral Innovation System of the Dutch Vegetable Breeding Industry

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ABSTRACT

In a number of studies, the Dutch vegetable breeding industry has been described as a highly innovative sector, but the root causes for its innovativeness have not yet been analysed systematically. In order to understand the factors that affect innovation and business performance, the Sectoral Innovation System (SIS) framework was used to analyse the linkages and interactions among the different actors in the Dutch vegetable breeding industry. Within SIS, five interacting domains are recognized and analysed: the business domain, the research & education domain, the intermediate organizations, the market demand, and the infrastructure & framework conditions, resulting in an integrated picture of the innovation system. It was found that the business domain, the research & education domain and the intermediate organisations do not only show an outstanding individual performance, but more importantly, they closely collaborate via public-private partnerships (PPP), research consortia, etc. It is shown that especially the cluster characteristics of the Dutch vegetable breeding industry, i.e. the geographical proximity and the high level of intra- and interconnectivity within and between domains, induces an intensive knowledge flow, a key indicator for the innovation level of a sector.

1. Introduction

After one century of development of the plant breeding business, the Netherlands has become the major exporter in the world of starting materials of plants, representing an increasing export value of 2.5 billion euro [1]. Dutch companies enjoy positions as global market leaders in plant reproduction material (seeds, cuttings, plantlets for ornamentals, potatoes, flower bulbs, grasses, and vegetable seeds). This position is based on craftsmanship, entrepreneurialism and innovation, and as a result the Dutch breeding industry is cited as one of the most innovative in the world [2]. Particularly in the vegetable breeding sector, companies with their basis and main premises in the Netherlands account for about one third of the worlds' vegetable seed exports and one eighth of the world vegetable seed imports [3]. This makes the Netherlands both the largest vegetable seed exporting as well as importing country. Over the past three decades, the vegetable breeding industry has become more and more consolidated due to many mergers and acquisitions. As a result the top ten vegetable breeding companies now account for over 85% of the vegetable seed market in the world [2], and most of these top ten companies originated in the Netherlands or have important R&D facilities in the Netherlands. This successful industry is playing important roles in the Dutch public domains related to food, agriculture, trade and the environment [4], as its innovations in this first phase of food production and food processing finally affect the whole supply chain [5]. It is, therefore, of particular interest to uncover the underlying factors that made the Netherlands outstanding and the most innovative in this field, so that other industrial sectors may benefit from this. Although the major task of breeding companies is developing new cultivars, innovation here is more than just developing cultivars. It also includes, new ways of organization, marketing, production and sales.

In a number of studies, the Dutch vegetable breeding industry has been described as a highly innovative sector, but the reasons for its innovativeness have not yet been analysed systematically

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[5–8]. Generally speaking, the development of new products and processes is not only based on the creativity of the individual researcher, entrepreneur, company or research institute, but rather the result of interaction and co-operation within a much larger system [9]. In other words, innovations are dependent on the interaction between the proprietary and external knowledge stocks of stakeholders in the system [10]. Connections across firms and industries have been shown to be fundamental to competitiveness, productivity, and (especially) to the direction and pace of new business formation and innovation [11]. Successful innovations require a collective effort to join together people, ideas and targets that were previously separate, and an effective networking among heterogeneous entries spanning various markets and technologies [12]. In this study, we used the framework of the Sectoral Innovation System (SIS) that was derived from the National Innovation System (NIS) model of Arnold and Bell [13], and we further developed SIS by putting more emphasis on the knowledge flow within the system [14].

The paper is organized as follows. In Section 2, we introduce the theoretical framework of SIS. In Section 3, on research context and methodology, the methods of data collection and analysis are described. Then in Section 4, the results from different domains of the Dutch vegetable breeding industry are presented, and in the final Section 5, we present the integrated picture of the SIS of this industry, in the discussion and conclusions.

2. Theoretical framework

Innovation is widely recognized as one of the major drivers of business success. Theories on innovation have gradually expanded their focus and complexity, beginning with the individual company or entrepreneur, and moving to a broader view on the environment and industrial sector in which the company operates, and finally encompassing the national system of regulations, institutions, human capital and governmental policy [15]. The NIS approach is based on the premise that understanding linkages among the actors involved in innovation is key to understanding their innovative performance. From this perspective, the innovative performance of an economy depends not only on how the individual institutions perform in isolation, but also on how they interact with each other as elements of a collective system of knowledge creation and use, and on their interplay with social institutions (such as values, norms, legal frameworks) [16].

Arnold and Bell [13] have developed a framework for NIS that is simple and integrative, including all NIS actors, such as companies, universities, research institutes, technology transfer agencies and technology policies [17]. Moreover, the model also takes institutional aspects into account, which are defined by new institutional economics, such as trust levels, standards, norms, rules or laws, etc., and also the typology of actors within an innovation system [18,19]. In recent years, the NIS framework has been used to analyse certain countries, such as all OECD countries [20], Norway[16], China [21]. In other cases, the focus was on the innovation system around a new technology, such as biotechnology [22–24], but also industrial sectors, such as the cocoa industry [25], copper mining industry [26] and IT industry [27]. In this study, we applied the SIS approach for the analysis of the vegetable breeding industry in the Netherlands. Cohen and Levinthal [10] showed that the interaction between proprietary and external knowledge stocks is important to the performance of a SIS. We therefore further developed the model of Arnold and Bell [13] by putting more emphasis on the knowledge flow within the system.

For the analysis of the Dutch vegetable breeding industry, we evaluated the five principal domains that constitute SIS of the Dutch vegetable breeding business. We analysed how the flow of knowledge is organized between: 1) The business domain, with a focus on breeding companies that apply and use codified knowledge and produce mainly tacit knowledge; 2) The research & education domain, with a focus on the professional and higher education and research institutes that produce and transfer codified knowledge; 3) the intermediate organisations that stimulate knowledge transfer and application; 4) The market demand referring to the final demand from consumers and intermediate demand from other actors in the production chain; 5) The infrastructure and framework conditions that include the more general aspects that can influence innovation, such as finance, taxation, and mobility. It is hypothesized that the available stock of knowledge and the knowledge flow generated in and among the first three domains play an important role in the innovation performance of the breeding sector. It is expected that the other two domains, market demand and infrastructure & framework conditions influence this process. The arrows in the theoretical framework (Figure 1) represent the main flows of knowledge. In section 4, the five domains of the Dutch vegetable breeding sector will be analysed in more detail.

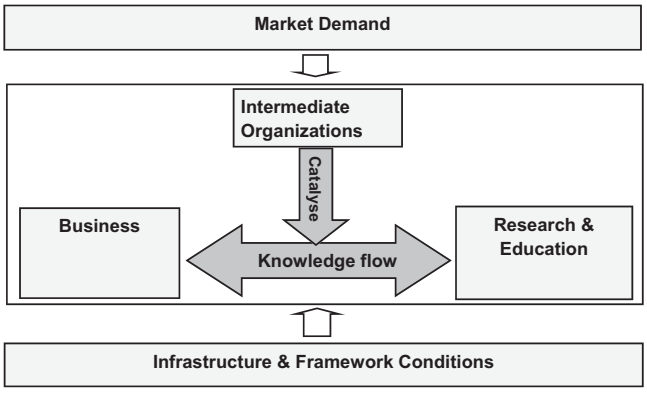


Figure 1. Theoretical framework for a sectoral innovation system
Source: adapted from Arnold and Bell [13].

3. Research methods

To ensure the validity of data collection and analysis, we have used a triangulation approach, by looking from different angles at the same phenomenon, and by using different data collection strategies and data sources [28–31]. We applied different data collection strategies for the business domain, research & education domain, and intermediate organisations domain. Archival data, such as time series of fiscal statistical year books from both domestic and international sources and regulations and governmental documents of the breeding industry, were checked, summarized, and compared.

In analysing the business domain, the Dutch vegetable seed sector appeared to be highly consolidated with only 28 companies active in the vegetable seed market. Many of them are only active in producing and selling seeds. Only ten companies could be identified as integrated seed companies that were active in breeding, seed production, and sales, and had a reasonable size (> 10 employees). All other companies in this seed sector were either smaller or only active in trading seeds. The integrated seed companies were either private family-owned companies or part of large multinational companies (Table 1). We visited and interviewed the senior managers of all 10 companies, using a semi-structured interview and questionnaire. In each of the visited companies, one or two senior managers were interviewed for 1-2 hours and asked to fill in the questionnaire. The following six aspects were discussed: 1) history and current organization of the company, 2) business

Table 1
Overview of vegetable breeding companies in the Netherlands in 2011.

	Private family-owned companies	Part of multinational companies
[1]Large	• Rijk Zwaan • Enza Zaden • Bejo Zaden	• Monsanto Vegetable Seeds • Syngenta Seeds • Nunhems (Bayer Crop Science)
[2]Small	• Pop Vriend Seeds • Agrisemen	• Nickerson-Zwaan (Vilmorin & Cie) • Takii Europe (Takii Japan)

[1] Large: with more than 1000 employees; [2]Small: with 10-100 employees

environment, 3) innovation strategy and input, 4) company and personal network, 5) absorptive capacity, and 6) innovation and business performance.

For the research & education domain, we interviewed researchers from the Plant Sciences Group of Wageningen University and Research Center (Wageningen UR), which is the most important research partner for the Dutch vegetable breeding companies. Feedback on the impact of the research & education domain for the vegetable breeding industry was also collected in the interviews with the breeding companies.

Publications and citation data of scientific publications in plant breeding and plant biotechnology were used to identify the international position of Dutch research in this field. Based on the search profile of Borsi and Schubert [32], publications and citation data were taken from Thomson–Reuter's Web of Science (WoS) from 1945 and onwards. The publications that were relevant for the seed business were chosen to be: plant genetics, plant molecular biology, and plant breeding. We extracted the top 1% of all the publications based on their citation indices. We found that all top 1% cited papers fall into the period of 1990 to 2005. To avoid this bias we divided the whole period into four periods: 1945 through 1980, 1981 through 2000, 2001 through 2009, and 2010 through 2012. As an objective parameter of scientific quality and leadership closely linked research collaborations materializing in high impact papers written by co-authors from research organizations of more than one country were counted. Finally the linkage data were entered into UCINET [33], a software tool for social network analysis.

In addition we conducted interviews with experts from stakeholders in intermediate organizations, e.g. governmental agencies and intermediate organizations, such as Naktuinbouw, Plantum, and The Centre for BioSystems Genomics (CBSG), to gain information from all stakeholders on the innovation system of the Dutch vegetable breeding industry.

4. Results

4.1. Business domain

The business domain of the Dutch vegetable breeding industry was found to be highly consolidated, globalised, innovation driven and to have co-evolved with the supply chain. It comprises of 10 integrated companies responsible for the majority of innovations and new products in this field.

4.1.1. Historical background, development and consolidation

The commercial production and sales of vegetable seeds in the Netherlands started over 150 years ago with the foundation of Sluis & Groot in 1867 in Andijk, a small village in the province of North Holland. Later on the company moved to Enkhuizen after the establishment of the first railway between Enkhuizen and Amsterdam. Nowadays, Enkhuizen is still home to a number of important vegetable seed companies, but also in other parts of the Netherlands concentrations of vegetable seed businesses have developed, e.g.

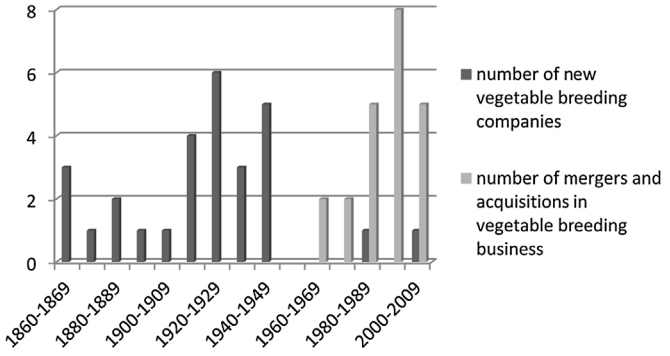


Figure 2. Evolution of the vegetable breeding business in the Netherlands - Number of new vegetable breeding companies and number of mergers and acquisitions over the past 150 years
Sources: [38]; websites, authors.

in the Westland region near Rotterdam and in the southern provinces.

Before the Second World War, development of new cultivars was done by growers and pioneer seed trading companies. The production and sales of seeds as well as the selection of better cultivars were done by the same company and when more and more companies entered the market, a vibrant seed business emerged. Figure 2 shows that there was a continuous growth of the number of seed companies from the 1860s to 1940s.

Since the Second World War, companies involved in seed selection transformed into professional plant breeding companies, in which science-based breeding became the core activity. The experiments of Gregor Mendel in the later part of the 19thcentury gave rise to the laws of heredity and formed the basis for extensive scientific research into the inheritance of traits in plants. A major breakthrough was the development of the hybridisation system leading to improved plant vigour and efficient protection of varieties [34]. Based on hybrid plant breeding technologies, pioneer companies such as Bruinsma introduced the first F1 hybrid tomato in 1946, Pannevis introduced F1 cucumbers in 1957, and Rijk Zwaan and De Ruiter produced their F1 cucumber cultivars in 1958. These companies usually made use of half-materials derived from pre-breeding in research institutes such as the Institute for Horticultural Plant Breeding (IVT) in Wageningen. The success of breeding companies was highly dependent on well characterized genetic material (germplasm) that needed to be accumulated and characterized over a long period and by specialized R&D personnel that developed the new cultivars. As a result, the threshold for new entrants was and still is very high. After 1945, no new vegetable breeding companies were founded, except Takii Europe, a subsidiary of the Japanese breeding company in 1984 and Agrisemen, a spin-off company of Syngenta in 2001.

The discovery of the double helix structure of DNA by Watson and Crick in 1953, contributed to the development of molecular tools for plant breeding like genetic modification (recombinant DNA technology; transgenesis) in the 1980s, and 'marker assisted selection' (MAS), and other 'molecular marker' technologies in the 1990s [8]. Biotechnology offered great opportunities, but also required more investments and was highly knowledge-intensive. The formation of Zaadunie in 1963 marked the starting of a wave of mergers and acquisitions, which peaked in the 1990s, with the aim to achieve economies of scale for capital and knowledge intensive investments (Figure 2). As a result the Dutch vegetable breeding industry was consolidated to the present number of about a dozen companies.

The merger and acquisition history of the Dutch vegetable breeding industry is complex. We show Monsanto, the largest

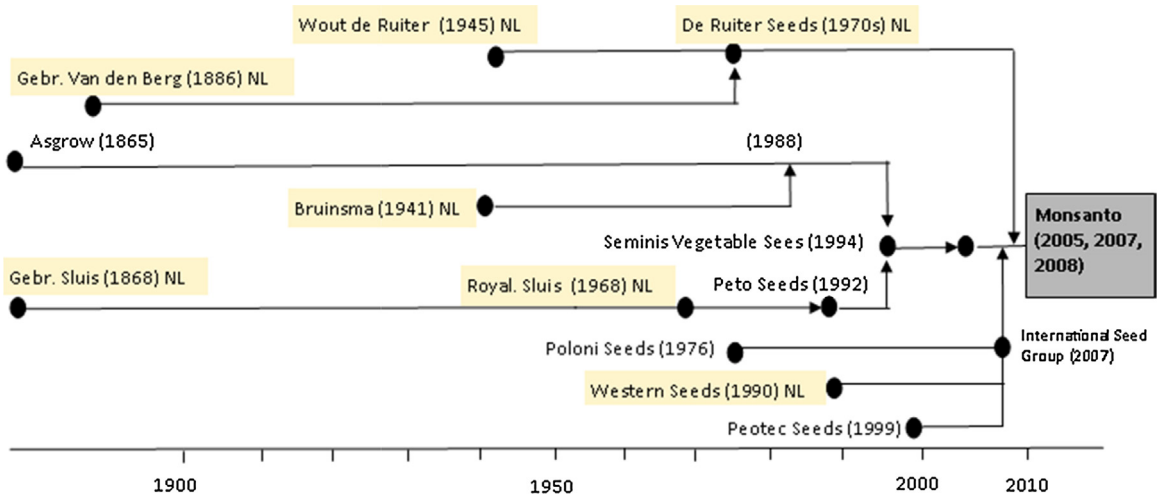


Figure 3. Historical overview of mergers and acquisitions that led to the current Monsanto vegetable breeding business
Sources: information from interviews and websites.

vegetable breeding company in the world, as an example (Figure 3). Monsanto became active in the vegetable breeding business only recently in 2005, when it acquired the Mexico-based company Seminis, at that time the largest vegetable breeding company. However, Monsanto's vegetable breeding business in the Netherlands can be traced back even to 1868. Dutch breeding companies were acquired and merged mainly domestically (e.g. Van den Berg Brothers was acquired by De Ruiter Seeds) from the 1960s until the 1980s, when the F1-hybrid technology became dominant in breeding [35]. After 1980, a large number of international mergers and acquisitions occurred, at the time that biotechnology and molecular breeding became important.

As a result of all mergers and acquisitions of the last decades, the vegetable breeding industry has become much more consolidated with only a few, but big players in the world. Many of the top ten companies were founded and have their main activities or have important R&D stations in the Netherlands. Figure 4 shows the ranking of the main vegetable breeding companies in the world. The total turnover of these 10 companies in the professional breeding business was over 3000 million Euro in 2013, which was 85% of the world turnover [2]. Table 2 presents the links with or the presence in the Netherlands, indicating again the importance of the Netherlands in the vegetable breeding industry.

4.1.2. Globalization

The Dutch vegetable breeding industry has always been driven not only by developing innovative new cultivars, but also by trading seeds within an expanding international market. Figure 5 shows that the Netherlands is both the largest importing and exporting country in the world, whereas its exports are much higher than its imports, and also much higher than those of other countries. This reveals the fact that the vegetable seeds are produced in many different locations across the world, then imported into the Netherlands for processing and packaging, adding value, and then exported to growers worldwide. Nowadays, the breeding business is a global business, and all large companies have very wide international networks of commercial offices, research facilities and distributors. Furthermore, the globalization stimulates and enables breeding companies to access knowledge worldwide. Eight of the ten interviewed companies indicated that at least one of their top five most important innovation partners is not in the Netherlands. Their main foreign innovation partners are universities and research institutes, other breeding companies, and customers.

4.1.3. Innovation driven vegetable breeding companies

Plant breeding companies are well recognized for their high level of innovation. If we look at the total expenditures in R&D of all companies in the Netherlands, as expected, large companies like Philips, ASML, Shell, DSM and Unilever are in the top five. But positions 12, 16, 18 and 23 are taken by respectively Rijk Zwaan, Nunhems, Enza Zaden and Keygene (a Dutch plant biotechnology company, see Section 4.5.1), which all represent Dutch companies active in R&D in the plant breeding industry [36]. The Dutch plant breeding industry was reported to invest on average 15% of its turnover in R&D each year [2].

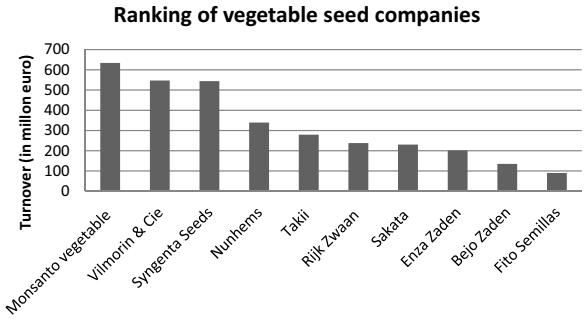


Figure 4. Turnover in 2013 of the world top ten vegetable breeding companies
Source: estimation from website, chamber of commerce, and personal information.

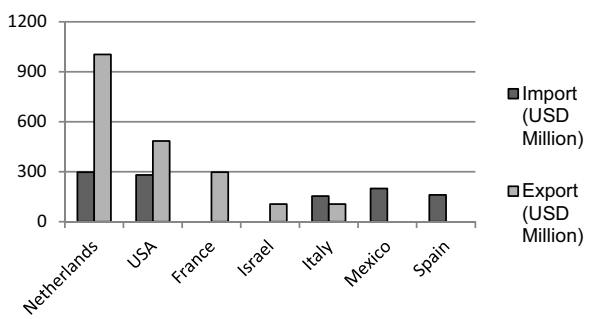


Figure 5. Top five countries exporting and importing vegetable seeds.
Source: [3].

Table 2
The world top ten vegetable breeding companies and their links to the Netherlands.

Top 10 company	Parent company	Original country	Links in the Netherlands
1. Monsanto vegetables	Monsanto	USA	Monsanto Vegetables has several roots in the Netherlands going back to Sluis Brothers in 1868 (details in Figure 3).
2. Vilmorin & Cie	Groupe Limagrain	France	Vilmorin & Cie acquired Nickerson-Zwaan in 1990 which is a Dutch vegetable seed company.
3. Syngenta Seeds	Syngenta	Switzerland	Syngenta Seeds resulting from a series of mergers and acquisitions, with a Dutch root that can be traced back to Sluis and Groot, founded in 1867.
4. Nunhems	Bayer Crop Science	Germany	Nunhems is a Dutch seed company founded in 1919, and acquired by Bayer in 2002.
5. Takii	Independent	Japan	Takii is a family-owned company founded in 1835 in Japan, and established their European subsidiairy in the Netherlands in 1984'.
6. Rijk Zwaan	Independent	The Netherlands	A family-owned Dutch company founded in 1924.
7. Sakata	Independent	Japan	Sakata was founded 1913, and established their trade office Sakata Holland in the Netherlands in 1990.
8. Enza Zaden	Independent	The Netherlands	A family-owned Dutch company founded in 1938.
9. Bejo Zaden	Independent	The Netherlands	A family-owned Dutch company with roots back to 1899.
10. Fito Semillas	Independent	Spain	A family-owned Spanish company founded in 1880.

Source: information from interviews and websites.

Based on our survey of all ten Dutch vegetable breeding companies (Table 1), basic information concerning size, turnover, age and research investment are presented in Table 3. Our analysis shows that on average now even 19% of the turnover is used for product and process innovation, and 32% of the employees are working in R&D. The R&D budget of one company was even 35% of turnover, and the number of employees involved in R&D can be up to 50% of total personnel. Such figures clearly illustrate the importance of innovation in this sector. The companies can be divided into different types. We differentiated private family-owned companies into two subgroups: small private (10 - 100 employees) and large private (more than 1000 employees) companies. In our analysis, Takii Europe was excluded from the group of multinationals, because it is a European subsidiary of a Japanese family-owned company, which is quite different from the other four multinationals that are publicly listed companies. In general, private-small companies are not only much smaller than the private-large and the multinationals in terms of number of employees, but also in terms of turnover, and especially in the number of R&D employees, which is only about 1% of the other two groups. Private-large companies are much smaller than the multinational companies, but have the longest history, highest R&D investments and highest percentage of R&D employees.

We also studied various R&D activities and the priority that was given to those activities (Table 4). As expected breeding and selection of new cultivars was given the highest priority by all companies, as it is the core R&D target of breeding companies. Genetic modification got the lowest priority, due to the limitations on the application of this new technology imposed by politics, legislation and regulations and the low public acceptance in Europe. Furthermore, there were differences between groups. The private-small ones gave less priority than other groups on using technologies, such as molecular markers, genomics and bioinformatics, and genetic modification. This might be due to their small size generating fewer funds for the acquisition of such capital intensive technologies.

4.1.4. Supply chain cooperation of the Dutch vegetable breeding companies

Breeding companies are the starting point of the vegetable supply chain. Their breeding activities affect all partners in the chain from grower, trader, processor, retailer to the consumer [5], and the value is multiplied in the various steps in the supply chain. Take one kilo tomato seeds as an example. The grower has to pay around 75,000 Euro per kg, from this kg of seeds he can harvest tomatoes with a value of 4,250,000 Euro, a multiplication factor of over 50 times. This value is multiplied again to a value in the retail of 8,500,000 Euro (Figures from 2011) [1]. This shows that in this sector the competition is much more on the quality of the cultivar and the seed than on the seed price.

Breeding companies are highly innovative and with their new cultivars affect the whole vegetable supply chain. But also the other stakeholders further downwards in the supply chain are recognized for their innovative strength. All breeding companies collaborate with processors of seeds, such as Incotec, and Holland Processing. They develop sophisticated equipment for seed processing and seed treatments to improve quality and efficiency. Furthermore, there are several collaborations between partners in the supply chain. For example, farmers are organized in cooperatives, such as Coforta, a cooperative of about 900 affiliated growers that fully owns the subsidiary company Greenery, which closely co-operates with the plant breeding companies and supermarkets, by collecting market information and delivering the demand to plant breeding companies. Supermarkets account for over 80% of the market share of vegetable retail in the Netherlands [37], and among the breeding companies that we interviewed, half of them collaborated with

Table 3
Basic information of two types of vegetable breeding companies in the Netherlands.

	Min.	Max.	Mean			
			Average	[1]Smallprivate	[2]Large private	[3]Part of multinational
1. number of employees	12	4,000	1,150	31	1350	2067
2. turnover 2010 (million Euro)	3.2	594.0	192.2	14.1	169.0	345.3
3. number of R&D employees	6	1,100	372	7	508	600
4. R&D budget (% of turnover)	9%	35%	19%	22.0%	23.0%	13.8%
5. R&D employees (% of total employee)	12%	50%	32%	31.0%	36.3%	29%
6.company age (year)	10	94	46	32	60.0	52

[1]Small: 10-100 employees; [2] Large: with more than 1000 employees; [3] Part of multinational, Takii Europe is excluded from this group, because it is the subsidiary of a family-owned multinational companies, which is quite different from multinationals

Table 4
Priority of research activities valued by Dutch vegetable breeding companies.

Research activities	Priority (1-7, 1-lowest, 7-highest)			
	[1]Private-Small	[2]Private-Large	[3]Part of multinational	Average
Breeding and selection of new cultivars	7.0	7.0	7.0	7.0
Use of molecular markers	5.0	6.7	7.0	6.3
Phytopathology research	4.0	6.7	6.8	6.2
Seed technology (e.g. quality control, seed coating, etc.)	4.5	6.7	6.0	5.8
Collection of new germplasm resources	5.5	6.3	5.8	5.7
Plant tissue culture(e.g. DH production)	2.0	6.3	5.9	5.1
Basic research (e.g. new breeding methods)	4.0	6.0	4.5	4.9
Genomics and bioinformatics	1.0	5.3	6.0	4.5
Use of genetic modification (GMO)	1.0	2.0	3.4	2.3

[1]Small: 10-100 employees; [2] Large: with more than 1000 employees; [3] Part of multinational, Takii Europe is excluded from this group, because it is the subsidiary of a family-owned multinational companies, which is quite different from multinationals.

supermarkets and used this market information in their strategy in developing new cultivars. Some breeding companies even signed exclusive contracts with supermarkets to sell specific varieties. Several breeding companies also indicated they have R&D projects with vegetable processors, such as vegetable packers of spinach, and producers of sauerkraut that use cabbage as starting material.

4.2. Research & education domain

The prosperous development of the breeding industry in the Netherlands is not only based on a well-structured business domain, but is also strongly supported by the agricultural research & education domain, which plays an important role in the knowledge flow that was essential for the development of the sector.

4.2.1. Consolidation of agricultural research and education

Agricultural education has a long history in the Netherlands. Already in 1876 the State Agricultural School (Rijkslandbouwschoool, the predecessor of the Agricultural University) in Wageningen was founded, with the objective to offer education to young people and to train them to become well-educated farmers [38]. It was amidst a crisis, caused by competing agricultural products from America in the 1880s, when other European countries, such as France and Germany resorted to protectionist measures, while the Netherlands chose to invest in research and education to improve competitiveness and productivity of the sector.

To that end in 1912 the Institute for Plant Breeding (Instituut voor Plantenveredeling - IvP) was founded for the improvement of agricultural crops. Another crucial development was the foundation of two new research organizations in the 1940's: The Institute for Horticultural Plant Breeding (IVT, Instituut voor de Veredeling van Tuinbouwgewassen), was a public research institute created in 1943, carrying out research programs ranging from fundamental plant breeding research to the development of cultivars, and closely cooperating with private plant breeding firms [39]. The second one was the Foundation for Plant Breeding (SVP, Stichting voor Plantenveredeling), which was established by the Dutch plant breeders association in 1948, with the aim of supporting the work of breeders and breeding companies with additional research that might result in commercial applications in the long run [38]. These research institutes have contributed significantly to the further professionalization of the breeding industry.

They were part of large investments in research and education in the post Second World War period, resulting in an extensive network of research organizations, agricultural schools at various levels of education, and extension organizations. Around 1985 more than 200 institutions were involved in agricultural and horticultural research in the Netherlands [40]. This agricultural knowledge system was internationally recognized and became a model for other countries. The system was known as the REE-tryptich which stands for the integration of Research, Education and Extension (in Dutch: OVO for Onderzoek, Voorlichting, Onderwijs) [5]. This organization has changed and consolidated dramatically over the past twenty years. The main reasons were the transformation of a funding basis from knowledge-push to demand-pull and the governmental decision to merge the research institutes into just a few major ones under a single management [40]. As a result, a major reorganization of agricultural research in the Netherlands took place from 1987 to 2004, culminating in the creation of Wageningen UR, an alliance of Wageningen University, the research institutes of the Dutch Agricultural Research Department (DLO), the experimental stations and the Higher Education Institute of Van Hall Larenstein [5]. The University groups as well as the research institutes responsible for research and education in plant breeding all became part of this organization. Apart from Wageningen UR, there are also a few other Dutch universities active in the field of plant biology and biotechnology disciplines, and relevant to the breeding industry. However, since plant related research including breeding, is largely concentrated within Wageningen UR, the analysis of the Dutch agricultural research & education domain here focuses only on this organization.

Currently Wageningen UR is divided into five expertise groups: (1) Plant Sciences, (2) Animal Sciences, (3) Agrotechnology and Food Sciences, (4) Environmental Sciences, and (5) Social Sciences. In each expertise group, departments for fundamental, strategic and applied research share the same central management. The applied research is close to the day-to-day practices of farmers and growers, and the strategic research is mostly organized along subsidized thematic research programs in which major stakeholders participate together with industry [7].

After the consolidation of Wageningen UR and a move to a central campus, interactions between research and education have improved significantly and synergistic benefits are clearly being reaped. Taking the Plant Sciences Group as an example, most of the 1600 researchers work at the same location in Wageningen since 2009, whereas they had multiple locations in the town and the rest of the country before merging. A recent peer review assessment, remarked that this situation creates daily opportunities to work together in the same laboratories and meeting rooms greatly facilitating the informal exchange of views and ideas [41]. Furthermore, a study of Terheggen and Leemans [42] showed that within Wageningen UR there are a relatively large number of joint multidisciplinary publications.

4.2.2. International collaboration and excellence of Dutch plant science

Wageningen UR has gained a prominent position within agricultural sciences in recent years. This can easily be deduced from an analysis of the scientific publication and citation indices. Among the most influential and widely observed international university

Table 5
Number of international top 1% papers in plant breeding and biotechnology in different periods.

Years	Number of top 1% papers	Number of international top 1% papers	% of the international papers
1945-1980	26	0	0%
1981-2000	108	12	11.1%
2001-2009	195	52	26.7%
2009-2012	89	38	42.7%
Total	418	102	

rankings, Wageningen UR ranked at top one position in the field of agricultural sciences [13,43], and top 22 position in the field of life sciences [44].

To visualize the international position of Wageningen UR among its peers, we analysed the worldwide network of authorships of all top 1% scientific publications in plant genetics, plant molecular biology, and plant breeding [32] from 1945 to 2012 (as explained in the methodology section). We found that the percentage of top papers with an international authorship increased substantially over time, and accounts for nearly half of all contributions in the latest period (Table 5).

These figures were used to map the global collaboration in plant breeding and plant biotechnology by using UCINET, a social network analysis software. In Figure 6, the nodes represent different research organizations, which published top 1% cited papers as a result of joint research with international partners. The lines in-between indicate that there were collaborations (joint publications) between the institutions. Based on the calculation by UCINET, it shows that the larger the node, the higher the betweenness centrality of a research organization is in terms of the global collaboration, which means the more central position it occupies in the network. Up to 2001, the top research organisations in the centre of collaborations were 1) John Innes Centre; 2) University of California Berkeley; 3) Mogen International; 4) Purdue University. The analysis up to 2009 shows that Wageningen UR rose to the second position after 1) French National Institute for Agricultural Research (INRA) and before 3) John Innes Centre; 4) Purdue University and 5) University California Berkeley. In the analysis up to 2012, however, Wageningen UR was holding the top one position as centre of collaboration with 2) University of Wisconsin; 3) INRA; 4) Cornell University and; 5) United States Department of Agriculture (USDA). This analysis clearly underlines the central role of Wageningen UR in the fields of plant breeding and biotechnology. It also illustrates an apparent increasing benefit to the research & education domain from the recent change in allocation of funding towards market driven research.

4.2.3. Students in agricultural sciences

For the development of a knowledge intensive industry it is important to have a healthy inflow of talented scientists. We, therefore, studied the numbers of students in agricultural sciences and more specifically in plant sciences. Figure 7 shows that the total number of students of Wageningen UR and its predecessors had increased over the years to over 7,000 in 1988. Then the number decreased substantially in the nineties extending into the first years of the new millennium, reaching a low level of about 4,000 in the years 1999-2000. This decrease was most prominent with male students, and since then females have overtaken males in student numbers. It is interesting that the recovery started around 2000, at the moment when the large re-structuring of the agricultural research organizations had resulted in the establishment of Wageningen UR, and was promoted as a university for life sciences instead of agriculture. Indeed, the dip in the number of students in the 80s and 90s may reflect the loss of traditional students interested in agricultural research and education and the replacement by a new student group interested in the study of life sciences. As a result the number of students is increasing substantially since then, with a total of about 10,000 again in study year 2014.

Looking specifically at the number of graduates in plant sciences, Figure 8 shows a decrease in graduates between 1990 and 2010. However, these low numbers are gradually recovering now thanks to the rapidly increasing number of international students. This was induced by the fact that the MSc programs are now all taught in English, and also have a high reputation, which attracts students from abroad. Although these figures are promising, the interviews with senior managers of breeding companies shows that the numbers of students in plant sciences are not yet sufficient to satisfy the demands for talented people needed in the breeding industry.

4.3. Intermediate organisations

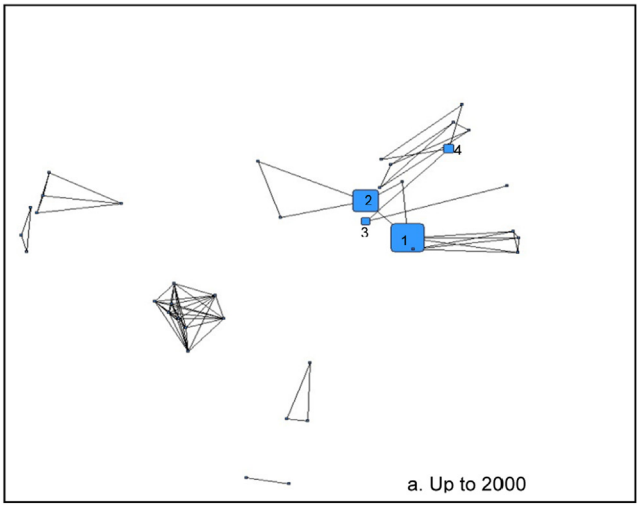
4.3.1. Public-private partnerships in agricultural research and education

Over the years, significant changes have taken place, not only in the research & education domain, but also in the interaction between industry, research institutes and education institutes. In the past, the classic flow of knowledge started with fundamental research at the university via strategic and applied research at governmental research institutes and experimental stations, to practical implementation via agricultural extension system following the REE tryptich system mentioned before [5]. Nowadays, the Dutch agricultural research & education domain has changed from this classical knowledge transfer model towards new concepts of co-innovation, where government, the public sector and the private sector work in close collaboration to create innovations (the so-called Golden Triangle). Several public-private partnerships have been established, in which various stakeholders work closely together in dynamic and open systems. Figure 9 shows such a model for the vegetable breeding sector.

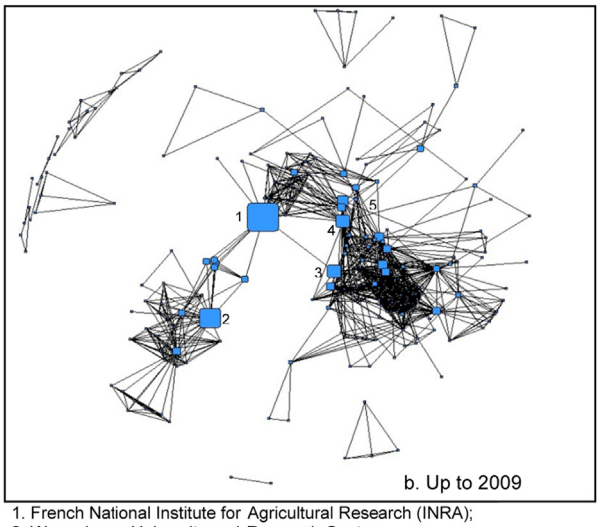
The exchange of knowledge is facilitated by a close interaction between various stakeholders in the education and research domain. An interesting example is the Green Knowledge Cooperative (GKC), an education consortium for the agricultural industry, with 13 'green' schools for primary and secondary vocational education, 5 'green' colleges (BSc) of applied sciences and Wageningen UR for academic education (MSc) and research (PhD). GKC focuses on making scientific knowledge accessible for educational programs of these universities and schools, and aims at establishing networks and shared facilities, characterized by strong and close linkages between research, education, industry and government [46]. Besides main-stream education, it also offers a broad range of special training courses for farmers and others involved in this sector. Life-long learning and knowledge diffusion in regional schools is encouraged between agricultural education and the breeding industry.

Co-innovation and knowledge dissemination is also facilitated between research institutes and the breeding industry by cooperative research programs in which both research institutes and breeding companies participate, partly funded by the government. Examples of such Public-Private-Partnerships (PPP) were the Centre for BioSystems Genomics (CBSG) and the Technological Top Institute Green Genetics (TTI-GG).

CBSG was a consortium of major Dutch and international breeding companies and top plant scientists working on three important food crops: potato, tomato, and brassica. It was a PPP in plant genomics including two universities, four research institutes, six vegetable breeding companies, five potato breeding companies, one potato processing company, one genomics technology company and two potato commodity boards. CBSG was founded in 2002 with a total research budget of 100M€ for 10 years.



1. John Innes Centre;
2. University of California Berkeley;
3. Mogen International;
4. Purdue University.



1. French National Institute for Agricultural Research (INRA);
2. Wageningen University and Research Centre;
3. John Innes Centre;
4. Purdue University;
5. University California Berkeley.

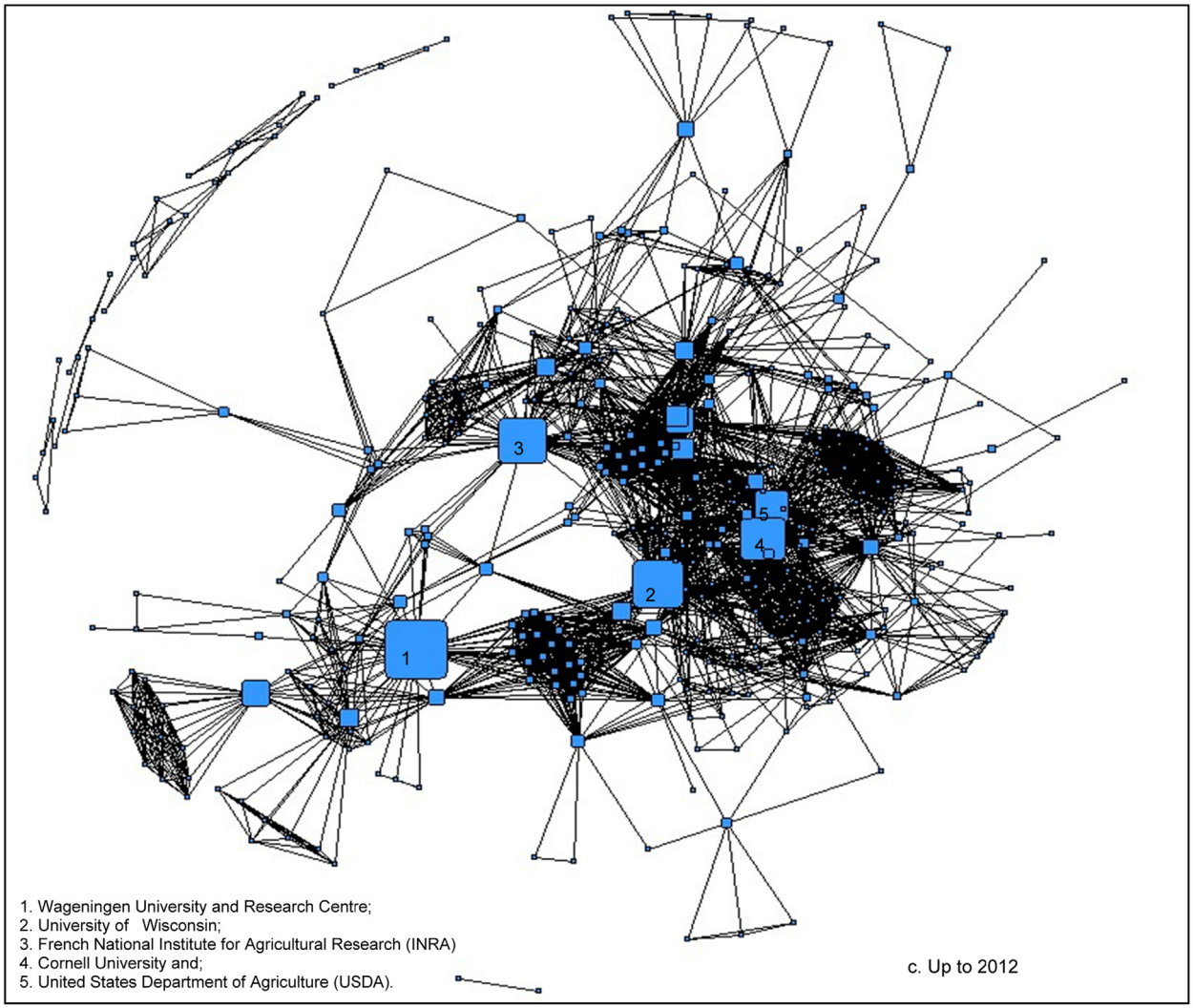


Figure 6. Global collaboration maps of plant breeding and biotechnology research a. up to.2001, b. up to 2009 and c. up to 2012.

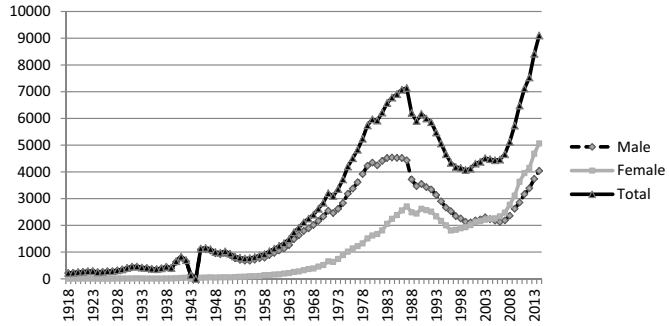


Figure 7. Number of students at Wageningen UR 1918-2014
Source: internal statistical numbers from KLV (Wageningen Alumni Network)
Note: The dip between 1940 and1945 reflects World War II.

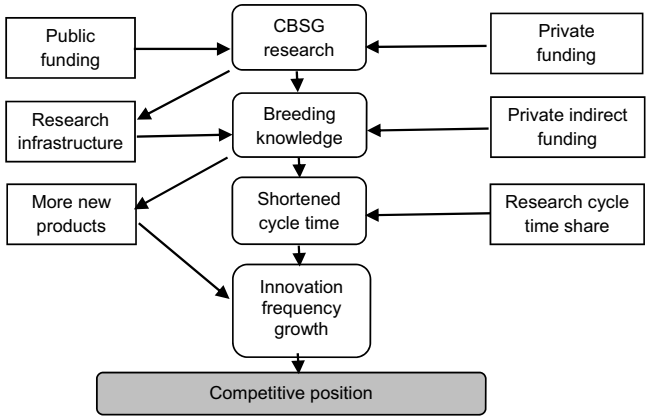


Figure 10. Organization of CBSG Research and expected impact on Industrial Partners
Source: Omta and Fortuin, 2010 [48].

The funding came from the Netherlands Genomics Initiative, the industrial partners and matching from the participating knowledge institutes. CBSG carried out plant genomics research using the latest, state-of-the-art technologies. The number of crops was restricted in order to maintain focus and to cover crops of greatest importance for the Dutch agri-food industry [47].

Omta and Fortuin [48] investigated the contribution of CBSG to innovation in the industry. The impact of CBSG research is visualized in Figure 10. The CBSG research organization was financed via a combination of public subsidies and private direct and indirect funding, in the expectation that investments in fundamental and strategic research projects would benefit the whole research infrastructure. Such improved public research infrastructure stimulated the industry to invest also in research programs linked to CBSG. Looking back the interviewed managers agreed that CBSG research enhanced their breeding knowledge, and expected more new products (improved cultivars) to be developed, and innovation cycle times to be shortened. Some companies even expected up to 30-40% time reduction in breeding programs and other companies indicated 5-25% cost reduction thanks to the research outcomes from the CBSG consortium. This will increase the innovation rate and enhance the competitive strength of the industry.

The impact of PPP's in the research infrastructure can be easily visualized by the changes in funding of the Plant Breeding Research Group of Wageningen UR (Figure 11). The budget for contract research, which was directly funded by companies, decreased from 20% in 2008 to 6% in 2011. During the same period, the percentage of funding via PPP's, which were funded by both companies

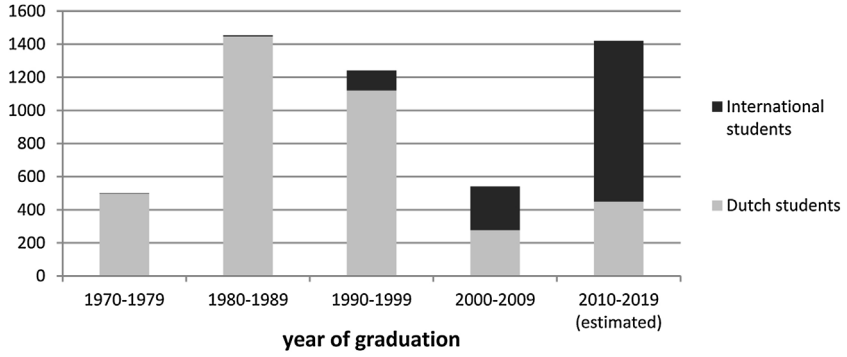


Figure 8. Number of graduates in plant sciences at Wageningen UR.
Source: internal statistical numbers from KLV (Wageningen Alumni Network)
Note: The number for the period 2010-2019 is an estimation based on the number of students currently present.

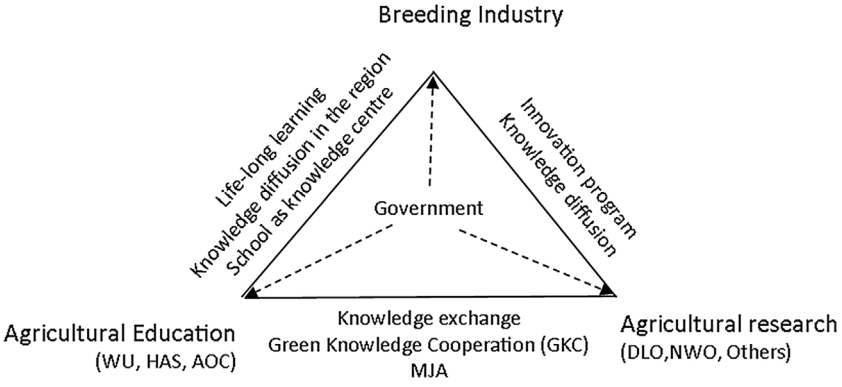


Figure 9. Public-private partnerships in the seed industry in the Netherlands
Source: Adapted from [45].

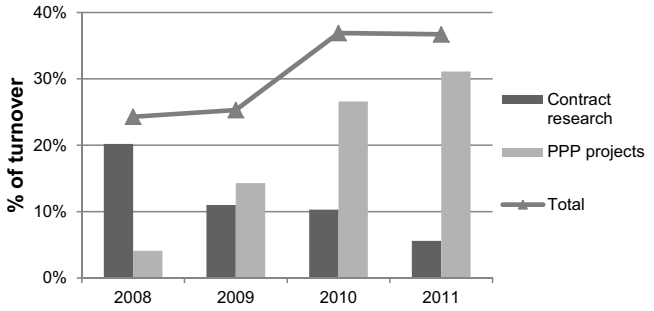


Figure 11. Contract research and PPP projects as percentage of total turnover of Plant Breeding Group of Wageningen UR from 2008 through 2011
Source: information from interviews.

and governmental subsidy, grew substantially from 4% in 2008 to 31% in 2011 [49].

Based on the success of the PPP's, in 2012 Dutch government decided to continue this innovation model through the creation of so-called Top Sectors, sectors that are selected on basis of their economic importance, in order to boost the competitive power of the Dutch economy. The plant breeding industry is represented in the Topsector Horticulture & Starting Materials and the Topsector Agri & Food. As a result many new consortia between industrial partners and knowledge centers have been established to further improve the research and education infrastructure.

4.3.2. Branch organizations

Plantum is the Dutch association of companies active in breeding, tissue culture, production and trade of seeds and young plants. It is not just a platform for member companies to exchange information, but it also plays an active role in important issues such as biodiversity, organic plant reproduction, crop protection, export and trade promotion, intellectual property protection, employment, legislation and legal affairs. With the aim of providing a better environment for innovation of the breeding industry, Plantum also facilitates the creation of the necessary knowledge infrastructure together with knowledge institutes and government. An example is the Technological Top Institute Green Genetics (TTI-GG) that was founded on initiative of Plantum. In our investigations we found that the interviewed managers of all breeding companies, both large and small ones, all were actively participating in Plantum and were positive about the contribution of Plantum.

Naktuinbouw, the Netherlands Inspection Service for Horticulture, was founded about 70 years ago by seed companies to control the quality of seeds, but also to support the industry to improve the quality of their business. Nowadays, Naktuinbouw is an autonomous public authority regulated by the Ministry of Economic Affairs, with the aim to promote and monitor the quality and identity of produce, processes and chains in horticulture. In that regard it is the official organization in the Netherlands to assess new varieties for registration purposes and granting Plant Breeders' Rights [50]. Through this platform, issues of seed quality can be discussed, providing the possibility to influence policies related to plant materials. Naktuinbouw has an obligatory inspection system that applies the European directives and legislation for propagating material for horticultural crops. Moreover, a series of voluntary quality inspections are performed that complement the statutory inspections and even place more stringent demands. Naktuinbouw is, finally, also involved in the development of systems to stimulate and spread knowledge in the breeding industry, such as by organizing training courses.

Seed Valley is a more recent initiative and refers to a specific area in the province of North Holland, home to many companies specialising in breeding, production and sales of high-quality seeds and basic plant material. This regional cluster also includes suppliers of services and equipment specific to the seed sector. Seed Valley was established with the mission to reinforce the economic position of the regional cluster, by investing in its image, and promoting the influx of skilled workers, innovation and sharing expertise.

4.4. High Market demand

As the global population will continue to grow to more than 9 billion in 2050, the demand for more, and higher quality food will increase dramatically. It is generally considered that crop production will have to increase by more than 50% in the next 25 years to meet the demand [51]. It was found that half of the enormous yield increase during 1947-1986 could be attributed to plant improvement by breeding and half to improvement of agricultural practices, in particular the use of fertilizers, crop protection and irrigation [52]. These agricultural inputs will become more scarce and expensive in the future, making the contribution of plant breeding even more important. Apart from a focus on yield, plant breeders also have to develop new varieties with resistances to biotic stress, which causes worldwide losses of about 130 billion US dollars per year, and varieties with tolerance to abiotic stress, as food production for 90 million people is threatened by drought, for 106 million people by flooding, and 900 million hectares of soil are affected by salinity [53]. Furthermore, several other factors have to be altered for the benefit of mankind: e.g. earliness, taste, size, nutritional value, firmness, shelf-life, plant type, labour costs and harvest ability [51].

In the vegetable sector, market demand is strong, as vegetables are important components of a healthy diet, and a sufficient daily consumption can help to prevent diseases. Based on FAOSTAT data, current production of the 15 vegetables studied has increased above 1980 levels ranging from 74% for sweet corn up to 259% for spinach and eggplant. On a *per capita* basis worldwide, consumption of all 15 vegetables rose by double digits, with cabbage the lowest (21%), and eggplant the highest (148%) growth [54]. As described above, this worldwide increase in demand offers good opportunities for the internationally oriented Dutch vegetable breeding business.

4.5. Infrastructure and framework conditions

4.5.1. "Polder culture" of collaboration

In our discussions of the main industry success factors with all the different stakeholders, the culture of collaboration with competitors and stakeholders was one of the most highlighted aspects. Within such collaborations they can learn from each other's expertise and can share costs and risks. As mentioned before Public Private Partnerships (PPPs) are widely found in the Netherlands. There are more than 40 PPPs in the field of life sciences, including CBSG and TTI Green Genetics [55] for the Dutch breeding industry. Thus, the Dutch breeding industry is characterized by fierce competition, but also by intensive collaboration. Apart from the aforementioned PPPs there are also unique business-to-business (B2B) collaborations between competitors to achieve certain calculated benefits. Intensive collaboration by small communities seems to be an interesting historical cultural phenomenon in the Netherlands. It was shaped over a long period since the 12th century and suggested have arisen from the need to reclaim and protect land (polders) from the threat of floods in river deltas and the risk of storms breaking dikes and dunes. It has been argued that this "polder culture" has become an integral aspect of the Dutch national identity [56].

A good example of such collaboration between competitors in the breeding business is Bioseeds, a strategic alliance between vegetable breeding companies. Since 1980 biotechnology became an

important new discipline in the R&D of breeding companies and in 1989 some companies founded Keygene, a plant biotech company. Its main focus was the development and application of new molecular breeding technologies that could speed up the breeding process e.g. marker-assisted breeding. Dutch-based breeding companies (e.g. Rijk Zwaan, Enza Seeds) formed the core of the collaboration with Keygene. Its success has attracted other foreign companies that became shareholder of Keygene more recently (Vilmorin & Cie, France; Takii, Japan) [5]. All four companies belong to the world top ten vegetable breeding companies (Figure 4), and in our interviews the senior managers of these breeding companies indicated that Keygene was recognized as their most important partner in innovation, and expressed their satisfaction with its achievements.

4.5.2. Governmental support for an innovative industry

The Netherlands as a small country with 17 million inhabitants has a relatively low number of scientists, but the output in scientific publications is about 3% of the worldwide production, ranking in position 10 in 2010. If output is calculated as number of publications per researcher, the Netherlands ranks number two (behind Switzerland). In such statistics, the USA (No.1 in total publications) and China (No.2 in total publications) only hold positions 15 and 18, respectively [57]. These numbers show the high research output and high quality of research in the Netherlands, based on a good knowledge infrastructure. As shown in previous sections this also holds for the domain of agricultural research, and more specifically for plant genetics and molecular genetics.

The Netherlands was also one of the first countries to establish a system for plant breeders' rights (PBR), already in the 1940's. PBR allows the breeder of the variety a monopoly position to assure the developer of the variety to have a good return on investment. PBR is also an open innovation system, as all protected varieties are freely available for use in future breeding programs of all competitors involved in active breeding (the breeder's exemption). Since 1980 the introduction of biotechnology in the plant breeding industry has also initiated the use of patents to protect intellectual property. In 2009 the Dutch Plant Breeders Association Plantum initiated an international debate on the interaction and unbalance between the two intellectual property rights (IPR) systems [6,58], with the aim to find a solution for further stimulating innovation in this sector. This debate has resulted in the integration of a limited breeder's exemption in Dutch and European patent law in 2014. Moreover the leading vegetable breeding companies have founded the International Licensing Platform with the aim to grant licenses on each other patents on plant trait innovations in a FRAND (fair, reasonable and non-discriminatory) terms [59].

5. Discussion and conclusions

5.1. Integrated picture of Dutch vegetable breeding sectoral innovation system

Based on the analysis in the previous sections, an integrated picture of the Dutch vegetable breeding industry as innovative sector is presented in the framework of SIS in Figure 12. The various stakeholders as well as some main characteristics of each domain as derived from this analysis are mentioned in the SIS diagram. The most important finding of the present study is that there is a strong knowledge flow between the different domains of the SIS of the Dutch vegetable breeding industry which may explain its innovative power.

Within the business domain, the vegetable breeding companies have become more and more professional and internationally-oriented during a period of more than a century. They spend on average 19% of their turnover on R&D, and make use of worldwide available knowledge. This intensive knowledge input combined with a high absorption capability has led to a high innovation output, leading to high-quality new cultivars, and a high ranking of Dutch companies and research organizations in lists of Plant Breeders' Rights (PBR)/Plant Variety Protection (PVP) and plant patents. For example, breeding companies from the Netherlands hold 32% of all European PBRs, and they even account for 55% of all PBR's in vegetable crops. Specific examples are lettuce (67%), French beans (46%), and tomatoes (42%) [60,61].

The analysis over the past decades shows that the organization of the knowledge flow between the business domain and the research & education domain was re-organized in a specific way. From a more linear knowledge flow in the triptych of Research, Education and Extension to the integrated model of PPPs. This intensified collaboration between the public and private sector stimulating a continuous knowledge exchange between these two domains, is one of the key factors to explain the innovativeness of the Dutch vegetable breeding industry. Moreover, collaboration is enabled by the intermediate organisations, such as association, cluster, semi-government organizations, which are well organized, appreciated by all stakeholders, and playing an active role in this industrial sector. They not only provide a platform to link different stakeholders, they also improve communication, and stimulate co-operation and co-innovation. Some of these organizations also act as brokers between the industrial sector and governmental institutions at the national, European and global level.

The worldwide increase in market demand combined with the trend towards healthy food provides great opportunities for this breeding sector. Because most Dutch vegetable breeding companies are already operating internationally with their breeding, production and sales, they are very well positioned to anticipate the increasing demands for yield and quality, by developing new products.

Collaboration and knowledge exchange finds its basis in the so-called Dutch "polder culture". This culture is not easily transposed, but it may still be an inspiration for other countries, regions or industries as a rational approach. It can be found back in the way institutional conditions, such as regulations and legislation, are organised, and in the set up of innovative formats to collaborate within SIS. Dutch stakeholders are pro-active in this field. For example, the access to genetic variation is crucial for further innovation in breeding, but granting of patent rights on plants and plant traits conflicts with plant breeder's rights, in particular the breeders' exemption [6]. As described in Section 4.5.2, the main vegetable breeding companies have taken the initiative for an International Licensing Platform (November 2014) to allow access to each other's patented plant traits.

5.2. Conclusions and key success factors

The sectoral innovation system (SIS) of the Dutch vegetable breeding industry is characterised by an intensive knowledge flow among the different domains, which is based on innovation driven companies, outstanding research and education institutes, strong support from active intermediate organisations, and most importantly, intensive cooperation among the various domains. This well-developed and interactive SIS provides the conditions and innovation climate to create a well-performing industrial cluster in the Netherlands. There are a number of key success factors.

Firstly, the Dutch vegetable breeding cluster has developed with the help of government by supporting investing in agricultural training and research since the beginning of 20th century, the initiation of PBR system for new cultivars, and establishing quality control organizations since the 1940s. Most important is the intensive collaboration between private companies and public research organizations, facilitated by government subsidy programs within

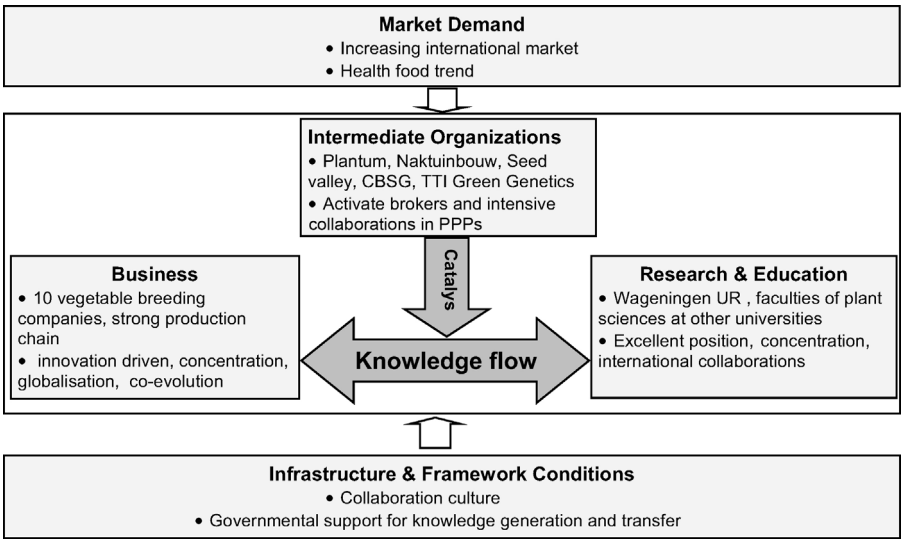


Figure 12. Integrated framework of the Dutch vegetable breeding sectoral innovation system (SIS).

the golden triangle. These policies shaped the sector to be even more focused on innovation and interactive collaboration.

Secondly, this sector benefited from geographical proximity. The Netherlands is a very small country, with most stakeholders such as breeding companies, research institutes, plant biotechnology companies, equipment suppliers, processors, customers all located within 100 km of each other. Being part of a geographic cluster allows companies to build better personal relationships and operate more efficiently in sourcing inputs, accessing information, technology and necessary institutions [62].

Thirdly, the outstanding position of the Dutch vegetable breeding sector is highly linked to the high level of interconnectivity. There are intense interactions between different stakeholders, including public-private partnerships, close links to research and education, and strong cooperation in the supply chain. These interactions are especially promoted by intermediate organisations and a favourable knowledge flow infrastructure, such as a culture stimulating collaboration and a well-functioning intellectual property protection system.

The SIS framework provides an integrated approach to analyse innovation of a specific sector systematically. It helps policy makers and other stakeholders to consider the advantages and disadvantages of innovation conditions in different domains of SIS: industry, research & education, intermediate organisations, market demand, and infrastructure & framework conditions. That can be learned from the innovative Dutch vegetable breeding industry example is the importance to stimulate knowledge flows among the different domains. This needs various stakeholders to understand the benefits of collaboration and to understand how to organise collaboration in a diversity of formats. Such collaborations should be supported by an excellent institutional infrastructure for research and education and the conditions that stimulate the creation of public-private partnerships, intellectual property protection, encouragement of innovation investments, and an emphasis on innovation in the industry.

Acknowledgements

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