The Coordination of Agricultural R&D in the U.S. and Germany: Markets Versus Networks

Barbara Brandl and Katrin Paula

Abstract Making money out of knowledge is a more difficult venture than it might seem due to defining characteristics of knowledge: non-rivalry and non-excludability in consumption. We argue that institutional attempts to overcome this difficulty in knowledge commodification shape the type of technological innovation in an economy. We suggest that two coordination types of R&D can be found: coordination by the market and coordination by networks. Empirically, our analysis is based on a mixed methods approach. We combine qualitative interviews with employees of seed companies in the U.S. and Germany, historical records, and descriptive quantitative analysis of yield developments in several crops. Finally, we compare market concentration in the U.S. and Germany. Our results indicate that coordination of agricultural R&D by the market (as in the U.S. since the 1980s) fosters innovations that are based on explicit knowledge. Furthermore, coordination by the market privileges large companies, tends to lead to a strong market concentration, and limits the development efforts on a few commercially beneficial crops. Coordination of agricultural R&D by networks (as in Germany), on the other hand, fosters innovations that are based on implicit knowledge and privileges medium-sized handcraft-based companies, which maintain innovation activities in a larger spectrum of crops. We conclude that the ban of transgenic seed in Europe cannot only be explained by the

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consumer protest but might also root in the institutional structure that coordinates agricultural R&D.

Keywords Agricutural innovation · Seed markets · Transgenic seed · Market concentartion

1 Introduction

Research and development (R&D), especially in the field of agriculture, was always of paramount importance for industrial nations. The political regulation of research and development in capitalist societies, however, is a precarious venture: while non-exclusive knowledge needs to be transformed into a commodity to enable capitalist accumulation, which per se is already a difficult endeavor, a prosperous economy does require a free flow of information to promote the development and diffusion of innovations. Traditionally, in the field of agriculture, R&D was mainly funded by the public. As we will see later, this is especially true for the U.S. whereas in coordinated economies such as Germany, private companies always played a bigger role in maintaining agricultural R&D activities.

Over the past decades however, the structure of public funding changed dramatically. Significant works of agricultural economists demonstrate a decline in the rate of growth on public spending for agricultural R&D and the shift in the levels of private investment in food and agricultural research compared to public investment [2, 14]. Still, the connection between public spending on R&D and the intended output, such as increased agricultural productivity, is far from clear. Nevertheless, in the current political discourse on national technology strategies only two predictors seem to matter in the evaluation of innovation: R&D expenditures of national governments or private companies and the amount of patents granted in a certain technological field [30].

In this article, we develop a more comprehensive view on innovation in the field of agriculture. Our theoretical perspective refers to the Systems of Innovation Approach, which traces back to the ground-breaking work of Nelson and Winter [32] who offered a new perspective on innovation and technological change. Their work "The Evolutionary Theory of Economic Change" is a fundamental critic on the classic economic model. While the classical model relies on diminishing returns resulting in an equilibrium with each firm making zero profits, Nelson and Winter argue that effective firms show increasing returns to scale, which arise from different types of dynamic behavior as learning by doing [4, 10]. Based on this perspective, the analytical focus shifts from the market mechanism and its potential failures to the firm itself in its interaction with its institutional environment. This also implies that technology development is not characterized by the inevitable unfolding of the most effective type of technology but that technology development is deeply shaped by path dependency rooted in the national innovation system. We do not claim that politics are superior to economy or technology. In fact, our core theoretical argument is that there is a co-evolution of economic institutions and technology development, which unfolds strong dynamics of path dependency [38]. An influx of literature, which examines this connection in a general way, already exists [22, 23, 29, 31]. However, little work has been done in order to get a better understanding of the influences of national innovation systems on the innovation potential in the field of agriculture [53]. Our study tries to advance this debate by focusing on the coordination of agricultural research in two national systems of innovation, the United States and Germany. We argue that, currently, two modes of coordination can be found and that these modes foster the development of different technology types: coordination by the market and coordination by networks.

2 The Difficulty of Organizing Knowledge Production

As we laid out in the introduction, we assume a fundamental incompatibility of knowledge and capitalist accumulation. To overcome this contradiction, institutions that organize the production and provision of knowledge within an economy are necessary. These institutions are the product of a strongly path-dependent process; they emerge from the co-evolution of technology development and institutional adaptation.

2.1 The Contradictions of Knowledge and Capitalist Accumulation

We suggest that there are four aspects of incompatibility between knowledge and its capitalist accumulation [8]. The first two aspects are prominently discussed in neoclassical theory of public goods: knowledge goods tend to be non-excludable and non-rival. To transform non-excludable, non-rival goods into excludable goods, private companies are using two dominant strategies [6]. First, they transform knowledge into a material good that is difficult to reproduce. The combination of software and hardware or the application of hybrid systems in the seed industry is illustrative of this process. Second, strong intellectual property policies, such as patents, enable knowledge protection. To effectively transform knowledge into a commodity, however, a twofold enforcement of intellectual property rights is necessary. Principally, the state needs to provide a mechanism for assigning and enforcing intellectual property rights. The holder of the patent rights must then have the resources necessary to discover when rights are violated and to take legal action against this violation. Therefore, companies usually need to allot considerable resources, such as the establishment of legal departments, to protect their formal intellectual property rights [36, 46]. The third aspect of the incompatibly between knowledge and capitalist accumulation emerges by virtue of the uncertainty in the research process [3]. This uncertainty, however, does not only apply to the research process itself but also to the commercialization of a potential product. The entrepreneur always runs the risk that a competitor is faster in granting a patent, which would temporally result in a market monopoly of the competitor. Therefore, a rational manager (based on cost-benefit analysis) lacks the incentive to invest in research and development. The problem of underinvestment increases the more basic research is involved. Kenneth Arrow [3] concludes that the state should fund research and deliver knowledge as a public good. The fourth aspect of knowledge, which hinders its capitalist exploitation, is somehow different since it cross-cuts the other three aspects. Knowledge can appear in different forms — it can either be explicit or implicit. Implicit knowledge may also be described as tacit, which means that this knowledge cannot be written down and is bound to a person and a certain context. Our argument is that the kind of knowledge predominantly involved in the production of knowledge goods not only influences the excludability of the goods but also the degree of standardization. Since explicit knowledge is knowledge detached from the context of its formation it becomes more or less universally applicable [17]. This means that disentangling the knowledge from a particular context and skills of individual workers makes it more likely that the knowledge good can be standardized. On the production side, standardization leads to savings (economies of scale) because, through explication, the production process and the worker become more manageable and efficient [9]. On the consumption side, standardization implies the expansion of the potential market [43].

In the last paragraph we described four aspects of knowledge that one must overcome to enable capitalist exploitation. Then again, by resorting to the necessary countermeasures, a contradictory dynamic might emerge. To avoid the problem of non-excludability, a state could enforce strong intellectual property rights but it then runs the risk of inducing severe market concentration. To counter the problem of risk aversion of private firms, the state could provide research and development as a public good but this might hinder private investment in this field. To prevent the danger of knowledge spread, a company could keep its production mainly tacit and context-dependent. However, this implies that the potential markets are limited and the firms remain depended on their knowledge workers. The institutional reactions to this dilemma differ highly among states. Different national institutional arrangements offer firms, universities, and other research institutions different sets of opportunities. Or as Hall and Soskice put it: "*there are important respects in which strategy follows structure*" [22, p. 15]. Hence, an in-depth analysis of national institutional arrangements provides the framework for a better understanding of the innovation potential of a nation. As mentioned, there is already a vast body of literature in which these questions are examined in a general way [22, 23, 29, 31], but little work has been done in order to get a better understanding of the influences of national innovation systems in the field of agriculture [53]. In the next section, we suggest two different modes of governance of agricultural R&D within a state: coordination by the market and coordination by networks. Although we make use of the influential framework by Williamson [57] and its further developments [21, 39], we do not think that the coordination types 'markets' and 'networks' exhausts all relevant variation which can be found empirically. In particular, the overuse of 'market' as an analytical concept to describe coordination processes entails a bundle of problematic aspects and fuzziness [7]. Despite these analytical problems, we argue that both analytical concepts market and network help us to develop a better understanding of the interdependencies of national innovation systems and technology development. We study differences in both coordination types with the following characteristics: the design of the intellectual property regime, the division of labor between private and public institutions, the type of intercompany relations, and the dominate type of innovation (mostly based on implicit or explicit knowledge).

2.2 The Coordination of R&D by the Market

Political economy scholars Hall and Soskice [22] argue that in liberal economies, such as the United States, the dominant mode of coordination is the market. This can be seen in several areas: To enable a free flow of labor, the labor market is less regulated than in coordinated economies. Also, the financial system is strongly built on the market mechanism. While banks are more or less outsourced financial departments of companies in coordinated economies, in liberal economies companies must acquire capital on the financial market. Another defining criterion of liberal economies is the competition between companies. This is incorporated by institutional mechanisms like anti-trust policies that limit opportunities for inter-company collaborations and technology diffusion. There are also limited opportunities for private companies to act as a collective when negotiating with government agencies [51]. Coordination of innovation by the market is essentially rooted on the opportunity to transform knowledge into a private (excludable and rival) good. For this transformation, institutions that foster the commodification of knowledge are necessary. Two mechanisms are especially efficient in this regard: enforcement of strong and comprehensive intellectual property rights for applied as well as for basic research and a public funding system that is driven by economic criteria such as royalties of patents or the number of university spin offs.

2.3 The Coordination of R&D by Networks

The second type of R&D coordination follows a very different pattern: the coordination by a network of collaborating firms and state actors. This type of coordination is in line with the general institutional architecture of coordinated economies. Whereas in liberal economies the institutional framework fosters the coordination of innovation by the market, the institutional framework of coordinated economies allows collective organization and bargaining of interest groups, like firms, within one industry [22]. The finance system in coordinated economies is based on banks and concentrated ownership, which allows a long-term horizon in financing of companies [52, 58]. While in liberal economies the competition of companies is a crucial feature, in coordinated economies the instructional framework allows technology exchange and cooperative standard stetting. The analytical concept of networks, as developed by economic sociologists, can help us understand the specific dynamic of technology development in coordinated economies. Williamson [57] stated that the amount of transaction costs determines whether markets or hierarchies are the ideal type of coordination. The economic sociologist Granovetter [21] criticized that neither markets nor hierarchies exist in the real world. This theoretical conception implies a radical empirical perspective on economic action and coordination. Based on the argument that the dichotomy of market and hierarchy does not reflect the reality, sociologist Powell [39] suggested a new type of organization: the network. He stated that next to hierarchies, networks are another powerful mechanism to (at least partially) overcome the threats of opportunism and bounded rationality. With his analytical concept of networks, Powell [39, 40] primarily addressed the new emerging patterns of economic organization, which arise from new technologies and new forms of communication. Despite Powell's different empirical context, we use his analytic insights on networks and apply it to the coordination of R&D in coordinated economies.

2.4 Observable Implications

In order to examine our theoretical argumentation, we will examine the case of the seed market. On the one hand, we will employ a historical perspective to outline the institutional process. On the other hand, we make some basic assumptions that allow us to generate two observable implications for the seed market case.

First, the coordination of R&D by the market privileges innovations that engender highly commercially beneficial production systems. R&D investments have to be amortized by trading and the possibilities for collaborations between companies are very limited. The resulting highly commercially beneficial products have two main characteristics: they contain privately appropriable knowledge and their production shows extremely high returns to scale. We are aware that both criteria are approximately true for every industrial production system. Our point here, however, is that the magnitude of both characteristics is much stronger in liberal production systems. Second, the coordination of R&D by the market encourages radical innovations. In reference to Hall and Soskice [22], we define radical innovations as innovations, which entail substantial shifts in product lines, the development of entirely new goods, or major changes to the production process. Based on this definition, we assume that radical innovations have a higher potential to result in highly beneficial products because they help firms to (at least temporarily) establish a monopoly. While the coordination of R&D by the market fosters fast technological progress and enhances the development of technologies that enable one single company to dominate the market, the coordination of R&D by networks has a stabilizing effect and privileges technologies that maintain the collaboration of existing companies in the network and prevents firms outside the network from participating. Therefore, incremental innovations, which are more reliant on implicit knowledge, are dominant. In the seed sector, the crop type determines whether a product is highly commercially beneficial. For being a highly commercially beneficial crop, three criteria must be met: the possibility to exclude non-paying users (e.g. through hybridization or utility patents), large markets, and finally an innovation which results in a new product that has superior agronomic traits. For the sake of global comparability, we choose two crops, maize and wheat, in the empirical part. We regard maize as a highly commercially beneficial crop. Maize has a natural copy protection through hybridization; thus, the infused knowledge becomes privately appropriable. Moreover, maize is predominately used as feed or energy crop. Therefore, the demand is strongly standardized. Finally, through biotechnology it was possible to create transgenic maize varieties, which bring paramount advantages (such as labor or pesticide savings) to the farmer. Conversely, wheat is an open pollinating cereal, which allows farmers to save their seed. At variance with that for maize, the demand for wheat is strongly diversified. One reason for this is agronomic: especially the winter varieties, wheat demands a stronger customization to different soils than maize varieties. This diminishes the market size for wheat varieties. Another reason is that the demand of bakeries and noodle producers is strongly diversified because they are in need of different characteristics of wheat. Until now, contrary to maize, transgenic wheat varieties did not bring neither agronomic nor economic advantages for the farmers.

Second, next to high profits highly commercially beneficial products show another characteristic: extremely high returns to scale in production and therefore concentration tendencies. In the seed sector, especially the production of transgenic seed shows high returns to scale because the costs for the development and the market approval for transgenic seeds are extremely high compared to the costs of multiplying the seed. However, not only the seed production itself shows high returns to scale but also the fact that genes which carry the desired feature (e.g. herbicide resistance) can be infused in multiple varieties. In accordance with most of the text books on competition theory, we assume that high returns to scale results in concentration tendencies [3, 11, 44].

H1: The innovation activity in highly commercially beneficial crops is higher if the market coordinates R&D.

H2: The coordination of R&D by the market leads to a higher level of market concentration than the coordination by networks.

3 Data and Methods

To validate our theoretical argument, we choose a mixed method approach. We combine a qualitative-historical perspective on national institutions with qualitative expert interviews, and descriptive quantitative data analysis. As we have laid out in the previous paragraphs, we assume that technology development is a co-evolutionary, strongly path-dependent process, which is shaped by the national institutional arrangements as well as from efficient firms which are able to adapt to theses frameworks. The historic perspective helps us to identify the path dependencies of the respective national innovation system by using the example of the seed sector. However, our analyses of the development and the dynamic in the seed industry in the U.S. and Germany are not only based on the works of historians but also on qualitative interviews with experts.[1]

Moreover, to examine our first observable implication, we use data from the Food and Agricultural Organization of the United Nations (FAO STAT) that maintain statistics on annual average crop yields and crop acreage by country. We use yield increase as an indicator of scientific research and innovation activity for the respective crop. Of course, yields are caused by more factors than improved seed, such as input factors (e.g. fertilizers, herbicides, and pesticides) and improved cultivation methods. However, the quality of seed is regarded to be a core factor of agronomic performance [12]. Although our primary comparison is between the U.S. and Germany, we include data on a few other countries to highlight the differences between the U.S. and Germany. To examine our second observable implication, we compare the levels of concentration in the agricultural seed sector in the U.S. and Germany using the Herfindahl Hirschman Index (HHI). The HHI is the most commonly used measure of concentration also applied by the U.S. anti-trust authority. It is an absolute measure of concentration, which reports of the sum of the squared market shares. For an HHI between 1000 and 1800, the market is considered to be concentrated. An HHI score above 1800 indicates substantial concentration [45]. Schenkelaars et al. [45] have calculated the HHI score for the U.S. and we use that score. Nevertheless, the main limitation for public research in agricultural markets is, generally, the availability of data [13]. Thus, there is no public available study on concentration of the German seed sector, probably because firm data is limited due to strategic reasons of the companies [13]. We try to overcome this problem by the use of two new datasets: First, we calculate the HHI using the database of the German Maize Committee to estimate the market concentration in maize seed. The German Maize Committee tests varieties and publishes the results to assist farmers in purchasing decisions. Additionally, we provide new data on the concentration tendencies in other seed varieties using seed approvals [Sortenzulassung] of the German Federal Plant Varieties Office [Bundessortenamt] for the time period 1990–2010.[2]

[1] We interviewed approximately 60 persons who were located in the U.S. and in Germany. As experts we regard mangers of breeding firms/agrochemical companies, breeders, scientists at universities in the field of Biology, members of governmental authorities, and farmers.

[2] Ideally, one would have one common data source. However, given the before mentioned data limitation, there is no data source that includes market data both from Germany and the U.S. A further limitation is that the seed approval procedure is not harmonized within the European Union. Hence, seed sorts approved in other European countries may also be traded in the German market. However, according to our interview partners, a German approval functions as a quality signal for the German market and therefore, bias should be small. This is not the case for maize, and therefore, we rely on the data from the Maize Committee for this crop. In general, reliable inferential data analysis would demand panel data on the firm level, which is not available for any country [13].

4 Results

4.1 The U.S. Case: Coordination of Agricultural R&D by the Market

The statement that R&D in the U.S. is coordinated by the market may provoke opposition, which would be very justified. Indeed, during the cold war area, huge parts of the U.S. public research and development activities were not driven by the market but by 'great visions' such as landing humans on the moon or the creation on a superior military complex [15, 41]. This context also applies to the enormous increase in U.S. crop yields during the 1940 and 1950s as well as the Green Revolution.

During the Cold War, public development of seed was not only understood as a means of securing domestic food supply but also as a weapon. Within a very brief period, the U.S. investments in wheat breeding made many countries (including the Soviet Union) dependent on U.S. wheat exports [1, 37, 59]. However, the research university in general and the land-grant system in particular underwent dramatic changes starting late 1970s [26, 49, 50]. The fundamental restructuring of the university system was caused by the political détente towards the end of the Cold War as well as the growing economic weakness of the United States. The economic shortcoming of the U.S. was related to the global diffusion of U.S. technology especially to its competitors, Japan and Germany [33, 47]. This change resulted in a university system that operates on the same logic as private companies: the market mechanism. This 'new type' of coordinating university activities is in line with the architecture of the institutional framework of liberal economies. Until the 1970s there has been almost no protection for intellectual property in the plant breeding sector.[3]

The Plant Variety Protection Act from 1970 implemented the first intellectual property certificates for crops. These protection rights were still rather weak compared to other countries as Germany. These weak intellectual property certificates were complimentary to the coordination of agricultural R&D by the state. Only some small areas of R&D were exempted from state coordination, such as the development of seeds in crops for which hybridization is possible, e.g. corn. However, the slow withdrawal of the state from coordinating agricultural R&D after the end of the Cold War as well as increased costs for seed development through biotechnology made a stronger intellectual property protection necessary. No other legislation was as groundbreaking as the Bayh-Dole Act of 1980. The Bayh-Dole Act renegotiated the question how to treat intellectual property that arises from federal public funding. Before Bayh-Dole, all research results and inventions from universities or public

(Footnote 2 continued)
Hence, we provide descriptive and preliminary results. Nevertheless, we carefully selected data available and believe we are able to show general tendencies.

[3]The Plant Patent Act from 1930 only applies to a-sexual reproduced plants, which means that basically all crops are excluded.

research institutions were considered to be public goods. Contrary to this open access policy, Bayh-Dole permitted universities to grant patents — even on basic research. In the seed sector the judgment 'ex parte Hibberd' of 1989 in accordance with the Bayh-Dole Act allowed firms and universities to grant utility patents on seeds or even single genes. The enforcement of stronger intellectual property rights not only allowed better appropriability of innovations, it also drove the commodification of innovation. Thus, intellectual property rights enabled firms to include innovation in a formal decision making process which is based on a monetary cost-benefit analysis as well as to enter into contracts with other companies on the use of certain technologies, such as cross licensing or mergers, and acquisitions. At the level of universities the coordination of R&D by the market had similar implications. As already mentioned, in the area of Cold War, research at federal funded universities was driven by 'great visions' rather than by economic profitability. In the seed sector therefore, a division of labor between the private and the public sector evolved [54]. The public sector was responsible for basic research and the development of seed for minor and less beneficial crops such as wheat or barley. The private sector focused on breeding activities among commercially profitable crops such as corn or cotton. In the 1980s, the restructuring of the university system blurred these boundaries. The subjection of university research to the market logic changed the criteria for academic excellence towards marketability [50]. The transformation manifested itself in the move of university researchers towards more commercially relevant crops [54], a decline in number of publicly employed plant breeders [5], and an increase in the proportion of research results in the public sector protected by patents [42]. During that same period, also the broader agricultural research and development structure changed. Agrochemical companies such as Monsanto or Dow acquired the majority of the medium sized seed companies and invested heavily in biotechnological research and development [24, 45]. Moreover, the number and scope of university-industry research collaborations expanded [19].

4.2 The German Case: Coordination of Agricultural R&D by Networks

As aforementioned, coordinated economies provide an institutional structure that creates space for collective organization and bargaining of interest groups. In the seed sector, two factors are of particular importance for understanding how the institutional structure affects the innovation process: the design of intellectual property law and the regulation of the market by state actors. Plant Variety Protection [Sortenschutz] is an industry-specific form of intellectual property protection that supports the cooperative structure of the sector. By the end of the 1920s, the Association of German Plant Breeders was able to enforce the implementation of intellectual property rights in the seed sector. This was very early compared to other countries [55]. The early implementation of intellectual property rights fostered the accountability of innovations, enabling German breeders to establish their brand names in the market. These early versions of plat variety protection from the 1920s were updated and, in 1953, the Plant Variety Protection [Sortenschutzgesetz] which allows breeders to access all existing varieties when doing research and covers the entire plant genome, was enacted [28]. Compared to the relevant U.S. legislations, however, farmers' rights under the German law were less comprehensive [27]. The German intellectual property right is not only complementary to the predominate type of innovation, but it also promotes cooperation amongst companies in the German seed sector. Another important aspect is that the German seed market is subjected to strong governmental regulation and artificial market interventions. The Federal Plant Variety Office not only grants plant variety protection but also makes decisions on market approval for the respective variety. The Federal Plant Variety Offices explicit objective is not the provisioning of variety diversity, but the adjustment of the market. The office has determined that it should be easy for farmers to decide upon the variety and that only high yielding varieties should be offered. Historically, this role arose during a period when increasing domestic agricultural production was the primary goal [16].

These characteristics of the German institutional framework foster the collaboration between medium-sized, mostly family-run breeding firms. The network does not only include mangers and breeders of collaborating firms, however, but also university researchers and members of governmental authorities (e.g. the Plant Variety Protection Office or the German Ministry of Agriculture). This network is strongly based on long-term personal relationships, which have been handed down over generations. Scientific societies, as well as industry networks in coordinated economies, are traditionally more oriented on the ideal of medieval guilds that they get privileges from the state as reward for their social service in education, standard setting, and the preservation of quality for goods and services. While guilds are deeply committed to a professional ethic and, therefore, have a high obligation to public goods, modern businesses clubs, or lobby groups try to enforce their group interests in the political arena. A second factor, which contributes to the stability of the majority of networks in coordinated economies, is the relatively small amount of members [34], which increases the accountability of individual action and, thereby, reduces opportunism. However, this stability also has a downside. It prevents external actors from accessing the industry. Therefore, the coordination of R&D by a close network hinders (or at least delays) the application of new (or just different) technologies. The closeness of the network in the seed sector leads to a paradoxical situation: ecological breeders encounter the same barriers as biotechnological breeders.

4.3 Innovation Activity in Different Crops

As we laid out in Sect. 2.4, we assume that some crops are more commercially beneficial than others. For the sake of global comparability we chose two crops, maize (highly commercially beneficial) and wheat (less commercially beneficial) to

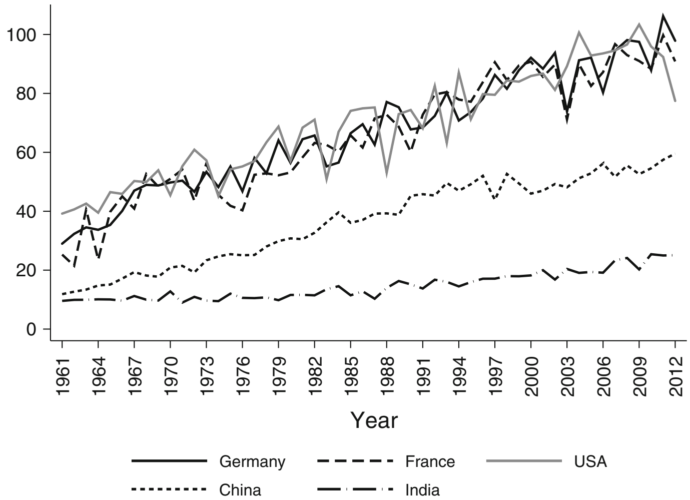

Fig. 1 Development of yield per hectare in maize (in 1000 hg), *source* FAO STAT, own calculation

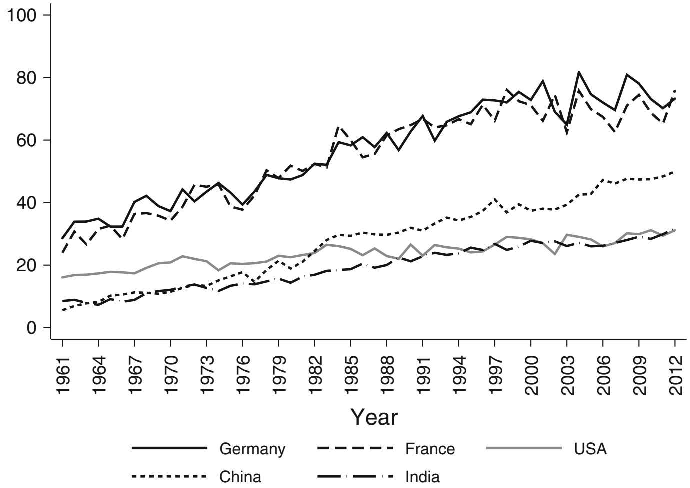

Fig. 2 Development of yield per hectare in wheat (in 1000 hg), *source* FAO STAT, own calculation

examine our hypothesis. In Figs. 1 and 2 we see the average development of yield per hectare hectogram in maize and wheat from 1961–2013.

It is important to look at the respective growth rate instead of comparing the absolute differences. Hence, the differences at the beginning can be explained by durable conditions such as the quality of soil or climate; however, the annual growth rates can basically be explained by an improved quality of seed. The charts show remarkable differences in the developments of yields in different crops. In China and India, the growth rate of wheat is much higher than in maize. This can be explained by the demand for the important food crop wheat and the high level of public funding in agricultural R&D in both countries [35, 48]. Alternatively, the demand of meat and, for that reason, for the feed crop maize rose only in the last decade and simply in China. In Germany and France, seed development mainly takes place in collaborating medium-sized breeding companies. In these countries, the demand for feed and food crops is equal and the annual rate of increase in maize and wheat is also similar.

However, in the U.S., the rate of yield increase in maize is much higher than that in wheat. We already mentioned that there are more reasons for the low wheat yields next to the quality of seeds; however, the U.S. wheat yields are remarkable low in an international comparison. They are much behind the Chinese wheat yield, whereas the Indian wheat yields are almost on the same level. For crops that are more commercially beneficial, such as soy or rice, the rate of yield increase is much higher in the US than in India [18]. The low U.S. wheat yields are even more surprising when we note that the almost the whole world was dependent on U.S. wheat exports between the 1940 and 1960s. From 1937 up to 1964, U.S. foreign trade surplus in wheat rose from 1.1 to 40.7 million tons, which was deemed to be four-fifth of the total world trade [1]. This incredible production increase was possible due to the immense public funding in this time [37, 59].

4.4 Market Concentration

While the U.S., as well as the global seed market, underwent a dramatic process of market concentration [24, 45], we could not find these tendencies in the German seed market. Schenkelaars [45, p. 18] shows that in 1985, the nine biggest companies in the seed market had a market share of 12.7%. This share rose to 16.6% in 1996. In 2009, the three biggest companies (Monsanto, DuPont, and Syngenta) had a share of 34%. In Fig. 3, we see that the Herfindahl Hirschman Index in the market for maize seed is much higher in the U.S. market. When we look at the firms that are active in the market, we see that the big agrochemical companies (such as Du Point Pioneer or Bayer) participate in the German seed market too but they do not have a dominating position. In Fig. 4, we observe that the HHI in the wheat and barley market is below 1000 (*dashed line*) during almost the entire investigation period. The concentration in the rapeseed market was at 2500 in the early 1990s. However, in the last 15 years it decreased dramatically with an HHI now being at about 1500 points. In comparison to wheat and barley, rapeseed is hybrid and therefore, commercially more beneficial.

As discussed in Sect. 2.4, we regard the higher market concentration in the U.S. market as a result of the organization of R&D. In the institutional context of the United States, companies naturally invest in technologies wherein private appropriation is possible and large markets are existent. Transgenic seed encounters both requirements, and herbicide tolerance and insecticide resistance are traits that make the seed superior in the context of the highly industrialized U.S. agriculture. In the

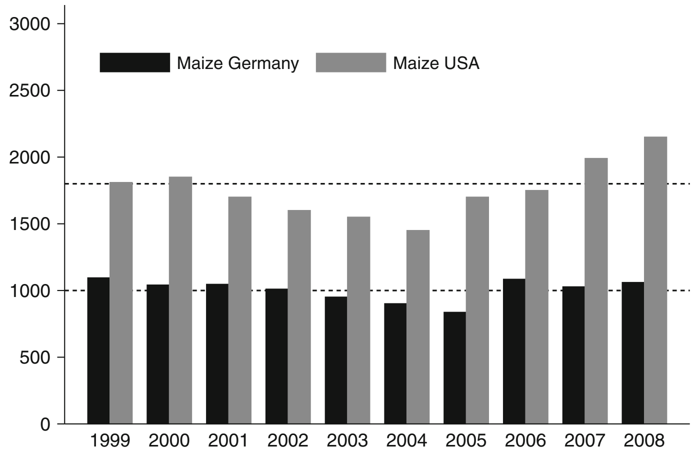

Fig. 3 Herfindahl Hirschman Index in USA and Germany, *source for Germany* data provided by German Maize Committee 2013, own calculation, source for the U.S.: Schenkelaars et al. [45, p. 43]

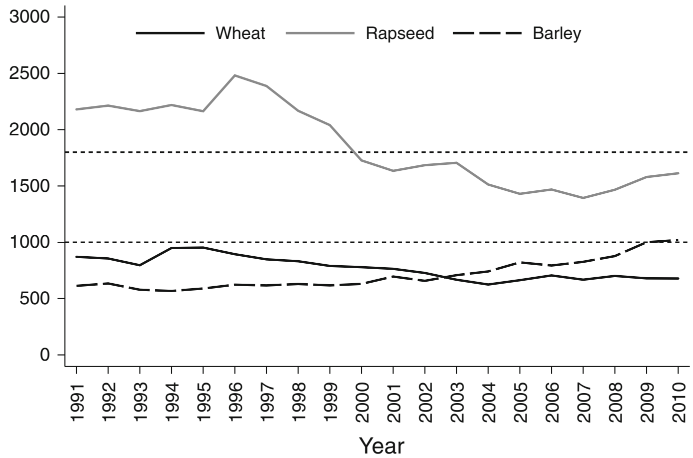

Fig. 4 Herfindahl Hirschman Index for non-maize crops in Germany, *source* data provided by the German Federal Plant Varieties Office, own calculation

production phase, transgenic seeds show extremely high increasing returns to scale because the costs for development and market approval are extremely high when compared to the costs of multiplying the seed. Then again in Germany, R&D in the seed sector is coordinated by a network. This network is based on stable personal relations, which hinder the diffusion of knowledge to competitors. The innovation process in the German seed sector is predominately based on implicit knowledge.

This implies that the innovations are not radical but incremental. The increasing returns to scale for each innovation step are much smaller than in the U.S. case and therefore, the concentration tendencies are much lower.

5 Conclusion

We have laid out the co-evolutionary process of technology development and institutions in the previous section. These theoretical insights may help us to develop a better understanding of the ban on transgenic seed in Germany. Contrary to the flat narrative that no transgenic seed is cultivated in Europe because of (irrational) consumers, who were able to organize efficient protest and boycott, we suggest that the ban of transgenic seed also has structural reasons. The German innovation system is based on implicit/ incremental innovations and collaboration. The adaptation of biotechnological methods would question this cooperative agreement of medium-sized breeding firms. Second, the technology historian Wieland [56] shows that the delayed and reluctant reception of biotechnological methods in the German industry can be explained by a path-dependent process, which was pre-structured by the chemical industry. The German industrys hostility towards biotechnology contradicts the early promotion of this field by the state. Graff, et.al. [20] lay out that U.S. American companies have a comparative advantage in biotechnological innovations, while German firms have a cooperative advantage in chemical innovations. Therefore, protesting consumers, farmers unions, and the German agrochemical companies become 'strange bedfellows' in fighting against transgenic plants. In reference to Hall and Soskice [22], we want to emphasize that there is not one best institutional arrangement, which leads to economic success in a late capitalist economies but there are some best (institutional) answers, which developed co-evolutionary to the requirements of technology and social forces. Hence, the structure of public R&D funding as well as political interventions, which aim to change the institutional frameworks as e.g. the global homogenization of intellectual property rights, have to orientate itself towards the national system of innovation rather than on a global agenda.

We would like to conclude with an illustrative case on how the very different organization of agricultural R&D in Germany and Canada responded to the same technical problem. Rapeseed was not suitable for human consumption until the 1970s. This changed when a German rapeseed breeder accidentally found an erucic-acid free rapeseed mutant. At that time, all five German rapeseed breeding companies cooperated with each other and secured government funding for further development. Each company, however, performed the last steps in developing a marketable variety on its own. In 1981, the first erucic-acid free variety was released. Cooperation among the companies was not only useful for pooling R&D resources; it was also necessary to reduce cross-pollination, which is especially high in rapeseed. It would have been unlikely that one breeder alone had developed a new variety. In Canada, an economy that is more consistent with the liberal type, the development of rapeseed varieties suitable for human consumption followed a very different path. The erucic-acid free varieties (Canola) were exclusively invented by public breeding programs in the 1990s [25]. Contrary to the German case, the Canadian government supported the application of transgenic methods to improve the rapeseed varieties. During the 1990s, transnational agrochemical companies purchased these public breeding programs. While Monsanto and Bayer dominate the Canadian rapeseed (Canola) market, the German market was still predominantly lined by the same medium-sized companies.[4]

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[4]The five companies are: NPZ Lemke, DSV, W.v. Borries-Eckendorf, Raps GbR, and KWS Saat. In 2011 Bayer acquired Raps GbR. Other companies perceived this acquisition very negatively. Until now however, this acquisition did not change the market structure. Thus, the market share of Raps GbR was very small, anyway.

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