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Centerless Governance and the Management of Global R&D: Public-Private Partnerships and Plant-Genetic Resource Management

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Abstract: Innovation is increasingly viewed as a key determinant of economic growth. Recent literature indicates innovation occurs at the local, regional, national and global levels. One such perspective suggests economic growth depends on developing an institutional framework that links local non-codified knowledge with global flows of codified knowledge. This article uses social network analysis, case study and vulnerability analysis to examine four functioning and inter-related regional and global pulse crop R&D networks. This article demonstrates that the public-private partnership is a critical institutional framework that links local assets to global knowledge flows.

Key Words: public private partnerships; innovation systems; social network analysis; pulses; research system

1. Introduction

Innovation is increasingly viewed as a key determinant of economic growth. There are a number of divergent perspectives on innovation. One posits that the private sector, at the firm level, is the primary source of innovation (Solow, 1956 and Arrow, 1962). Another firm-centric view suggests innovation is the result of endogenously developed knowledge occurring at the firm level but impacting at the macroeconomic level (Krugman 1998 and Romer 1990). Alternatively, one institutional approach examines the effect of economies of scale and scope on developing systems of innovation at the local, regional or national levels (Porter 1990, Lundvall 1992 and Nelson 1988). A more recent institutional perspective suggests that innovation is the result of interactions between university, industry and government actors or organizations at either the micro or macro level. This view posits that universities centre knowledge generation and diffusion networks by developing collaborative links between the three sectors and with the market (Etzkowitz and Ranga 2009). One refinement on that view is that innovation in inherently multi-level, drawing on resources and capacities at the local, regional, national and global levels. In that context, the key to economic growth is developing an institutional framework that connects local capabilities to global knowledge flows (Bathelt 2004 and Phillips 2002). One common theme that underscores the recent collaborative-oriented institutional and global perspectives is the emergence and increasingly important role of public-private partnership[1] (P3) organizations as leaders in forging the links between various organizations and networks to facilitate the knowledge generation and diffusion process (Bathelt, 2004 and Etzkowitz and Ranga, 2009).

The balance of this article is devoted to examining three interrelated and interconnected regional research and development (R&D) networks that collectively constitute the global pulse crop breeding R&D system of 248 actors. We use social network analysis to simulate alternative network configurations to test for resiliency of the systems. The primary focus of this work is to examine the P3 organizational format, an innovation in and of itself, and to determine whether it provides the structural integrity and linkages necessary for sustained innovation both in the three unique regional R&D sub-systems and in the global R&D system.

[1] These partnerships are sometimes called hybrid organizations.

Section two contextualizes the origins and theory of the P3 organizational format and its applicability to R&D network management. Section three offers an overview of the science and technology (S&T) and R&D dependent pulse breeding sector. Section four contains the theory of knowledge development and the methodology used in this paper. Section five presents the results of the analysis and section six reviews the strategic implications of our work.

2. State of the Art

Innovation is defined as not only mere 'invention' but, rather, as a broader and more significant process of turning new information into knowledge that can produce new goods, services or organizations that possess long-term staying power and material or social benefits within society or the economy (Phillips 2007). The process of innovation begins when new information is transformed into one of four types of knowledge. There are two types of codified knowledge, know-why and know-what, and two types of non-codified knowledge, know-how and know-who.

Each type of knowledge can be further delineated by their unique characteristics. Know-why knowledge is the product of a formal and collective process which is primarily concerned with articulating the scientific laws of nature. Much of this work takes place in universities and other publicly funded research institutions. From a plant genetic resource (PGR) perspective, each type of knowledge also possesses specific features (Phillips 2001, 2002). The disciplines of applied and theoretical genetics, molecular biology, biochemistry, plant physiology and genomics are in the domain of know-why knowledge. Know-what knowledge concerns facts and systematic details and procedures of both genetic crossing and the selection of desirable plant traits during the breeding process. Know-what knowledge is created in both public and private institutions and with the advent of PBRs and IPRs has become commoditized and integrated into increasingly sophisticated technology transfer processes. Know-how knowledge integrates the properties of know-what and know-why domains in plant breeding to produce new market-ready varieties. This process combines the knowledge developed at universities and technical schools and incorporates it with the skills derived from "learning by doing". This unique combination of skill and knowledge is contained within private or public institutions, is difficult to codify or transfer to other organizations and may be encompassed in closed community or proprietary processes. Know-who knowledge refers to the ability to identify and locate key practitioners who possess knowledge critical to a given transformation process. This type of knowledge is not codified and is embedded in individuals, institutions, and in networks or clusters engaged in similar research objectives. Due to the development of information and communications technology, knowledge development is no longer confined to institutions but occurs in widely dispersed networks characterized by multiple sites of knowledge development. In this environment know-who knowledge becomes an important component of the plant breeding process.

These particular characteristics of knowledge development and management tend to concentrate innovative activity within local, regional, national, economic and functional clusters or innovation systems that facilitate that transfer of information, knowledge and people between communities and organizations of various institutional configurations (Phillips, Boland and Ryan 2009). These characteristics are evident in research and development clusters such as Silicon Valley, the Boston Route 128 Corridor, North Carolina's Research Triangle, Western Europe's BioValley and Saskatoon's biotechnology community.

Gibbons (1994) identifies two unique and separate forms of knowledge production. Mode I production is described as a linear and institutional process that is dependent on the individual researcher for impetus in a uni-disciplinary research environment. Mode I knowledge generation largely conforms to the vertical/hierarchal form of governing. Mode II knowledge production occurs within "heterogeneously organized" networks that are organized around problems and solutions—as a result they are frequently transient in nature and horizontal in configuration. The nature of the resulting research is multi- and trans-disciplinary, which usually requires collaboration between universities, firms, groups, government research centers and public and private think-tanks. Mode II knowledge challenges traditional governing systems because the majority of communications and knowledge transfers tend to occur across traditional institutional boundaries, threatening the existing hierarchal structure.

Phillips (2007) suggests there are three convergent approaches to governing these types of knowledge production systems. The first is governing by regulation, which is the domain of the state and operates in the political arena via a command and control mechanism. The second is though transactions, where the market system supports and nurtures an exchange system. The third is collective governance—as the domain of the civil sector it operates in the social realm and is governed by consensual and voluntary relations and associations. This approach to governance is best exemplified in the work of Kenneth Boulding in his "social triangle" of governance, which posits that all societies and organizations are constructed on an interdependent mix of the three sectors—public, private and voluntary (Boulding, 1970). Picciotto (1995) converted this paradigm into economic terms, categorizing the state, market and civil authorities by the degree of subtractability/rivalry, excludability and voice of their respective outputs (figure 1).

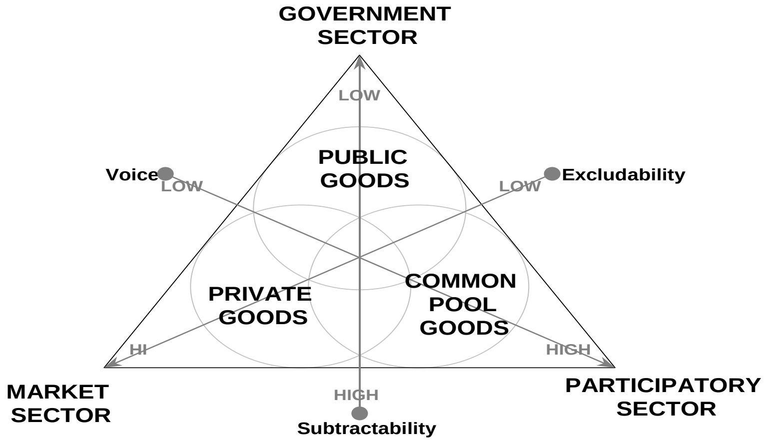


Figure 1: The Governance Triangle (*Source: Picciotto 1995).*

Institutions provide the "incentive structure of an economy" by establishing the rules and norms that govern the relations between the public, private and voluntary sectors (North, 1990). Institutions by design control and lower the costs of managing transactions in an environment of uncertainty and asymmetric information. Therefore, institutions are a key determinant to the profitability structure of economic activity (ibid). Each sector is best suited to provide a specific good (Boulding, 1970, Picciotto, 1995) (table 1). The government sector is best suited to providing public goods (e.g. defense or policing), which are characterized by low voice, low excludability and low subtractability.[2] The market sector is structured to provide private goods (e.g. clothing or automobiles) characterized by high excludability, high subtractability and low voice. The participatory sector by design provides common pool goods (e.g. R&D, market research and coordination), with low excludability, high voice and low to high subtractability.

Table 1: Typology of institutions by attributes			
Institution	**Excludability**	**Subtractability**	**Voice**
Public goods supplied by government	low	low	Low
Market goods supplied by the private sector	high	high	Low
Collective goods supplied by voluntary associations	low	Low to high	High

One form of collective action is the public-private partnership. From a definitional approach, a P3 refers to any collaborative engagement between public, private, and voluntary actors or organizations. A number of factors are responsible for the advent of the P3, including declining public revenue, technological advances, and increasing citizen participation and privatization efforts (Boase 2000). No one standard model exists for P3s; rather, they should be viewed as a process that allocates risk and reward on an equitable basis among key stakeholders.

There are a number of methods of contextualizing research-based P3s. One perspective postulates that three theories are required to explain the existence of research P3s (Hagedoorn 2000). First, transaction cost theory explains why some institutions might emerge in pursuit of lower cost of contract management and enforcement. Second, strategic management theory suggests that partnerships and networks permit firms to attain economies of scale and scope in their R&D endeavours. Third,

[2] Voice is the ability of a constituent to have their opinion heard by decision makers, this concept is from Albert O. Hirschman. Excludability is a situation where an individual can be prevented from consuming a good at little or no cost to the firm. Subtractability is where the consumption of a good by one individual does not prevent the consumption of that good by another individual.

industrial organization theory, which posits that knowledge is a public good, concludes that public-private collaboration is needed for cost sharing and commercialization purposes. Research P3s can be categorized by the type of knowledge developed—a formal structure is best suited for codified knowledge while an informal structured P3 appears best for managing non-codified knowledge (Spielman et al 2007). P3s may be categorized by their particular management function—some engage in network development and management while others are more directed to managing processes or projects (Klijn et al 2000).

3. Research Focus on the Global Pulse Production and Research System

One illustrative example where P3s are increasingly important is the global pulse research system. Pulse crops are an important source of plant-based protein, supplying about 10% of the world's total dietary intake of protein. The primary pulse crops are: lentils, peas, dry beans, chickpeas and faba beans.

The global pulse breeding system of 248 actors is comprised of 45 P3s, 107 government research centers, 83 universities and 13 private sector actors. The Export System, including Canada, the US and Australia, encompasses of 17 P3s, 27 government agencies and 22 universities. The European Union (EU) System has 27 P3s, 40 government agencies, 55 universities and 12 private firms involved in pulse breeding R&D. The Developing World System, including many African and South American countries, comprises 10 P3s, 41 government research centers, 17 universities and one private firm.

The Export System is primarily devoted to the production of exportable pulse crops. The EU System is a significant producer, consumer but only a minor exporter of pulses, while the Developing World System is a major producer, consumer and importer and exporter of pulse crops (Table 2). Appendix A provides a complete listing of actor name, institutional configuration, location and network affiliation.

Table 2: Production and exports of pulses, 2003-07, million tonnes

	Production		Exports	
	Volume	**% total**	**Volume**	**% total**
Export System	7,604	12%	4,292	45%
EU System	7,241	12%	1,640	17%
Developing World System	45,046	76%	3,570	38%
World Total	59,892	100%	9,503	100%

Source: FAOStat.org and Authors' Calculations

The process of plant breeding in general, and pulse breeding in particular, has been permanently altered by three ongoing and interrelated revolutions. First, plant breeding has evolved from a hands–on, experimental, supply-push process that historically was led by plant scientists in public agencies to become a globalized, technologically-driven, demand-pull, scientific process taking place in local, regional and national networks (Frey 1996). This process mirrors the distinction between Mode I and Mode II knowledge production (Gibbons et al, 1994). Second, the introduction of national and international intellectual property rights (IPR) regimes governing plant breeding, and in some markets for plant patents, has privatized most aspects related to plant breeding in the developed world and has triggered access and benefit conflicts over the acquisition and use of technology in the developing world where IPRs are not generally in use. Third, partly due to fiscal concerns and partly due to ideology, much of the funding of plant breeding has also been privatized, forcing research centres, industry groups and producer organizations into new funding and R&D relationships (Brennen and Mullen). The ongoing series of 'revolutions' within plant breeding has created what is often called the 'orphan' crop—one that is neglected by both public and private sectors due to small acreage or low profitability. Orphan crops exist in a virtual vacuum, where neither the public nor private sectors are capable of supplying the appropriate flow of innovations that can sustain production.

While pulses have many attributes similar to orphan crops (few national governments or private firms have invested much into research in these crops and most production until recently was undertaken by subsistence farmers), there is a vibrant and expanding production and export business in Canada, the US and Australia, representing a highly competitive multi-billion dollar global sector. Interestingly, the lead actors in this effort are not governments or industry, but producer and science led P3s.

4. Methodology

This study uses social network analysis (SNA) to illuminates previously invisible relations between actors and institutions in the networked and centerless global pulse research environment, as suggested by Mead (2001). SNA enables a researcher to identify the relative position, function and power ranking of individual actors, nodes and sub-networks in a quantifiable and graphical manner. SNA makes it possible to identify knowledge flows and stocks as well as under- and over-utilized individuals and organizations within a given network (Phillips, Boland and Ryan, 2009). As economic growth is highly dependent on linking into and manipulating the global flows of knowledge, SNA can identify the spatial coordinates of the institutions that possess the knowledge stocks and determine the direction of the flows of knowledge. Ryan (2008) suggests SNA can be utilized to deconstruct the institutional activities that are responsible for knowledge development.

Four measures of analysis are used in this study. One is related to network density; the other three are measures of centrality applied to individual actors (summarized in table 3).

Table 3: Typology of Centrality Measures

Measure	**Descriptor**	**Meaning**
Total degree centrality (TDC)	intra-network connectivity	An actor or principal with higher TDC is identified as a “hub” or “connector” within the network
Betweenness-centrality (BC)	Influence	An actor or principal with high BC is identified as a “broker” or “bridge” and can connect or disconnect groups within the network
Centrality Eigenvector (CE)	Power	An actor or principal with higher CE has multiple connections with others with multiple connections

Adapted from Ryan (2008).

Density measures the proportion of bilateral ties between actors against the maximum amount of ties possible. The objective is to identify and measure the ratio of interconnections within a given network. Density—which ranges from zero to one—is determined by dividing the number of actual bilateral connections into the maximum number of bilateral connections possible (Knoke and Kuklinski 1982). Equation one contains the density formula.

$$Density_{Local} = \frac{2L}{N(N-1)} \qquad \text{Equation 1}$$

Centrality measures the relative importance of an individual actor based upon their location within a social network. Total degree centrality is a ratio of the amount of actual ties divided by the maximum amount of ties. Ryan (2008) notes this measure shows the degree to which one actor is connected to other network actors, in effect determining the level of intra-network connectedness. An actor with a measure of zero is not connected within a network (i.e. is an isolate), whereas a measure of one indicates an actor is connected to every possible actor in the network (Phillips, Boland and Ryan, 2009). A higher total degree centrality implies a higher level of network activity (Mote, 2005). Equation two contains the total degree centrality formula.

$$TotalDegreeCentrality = \frac{\mathrm{td(x_i)}}{2*(\mathrm{N}-1)} \qquad \text{Equation 2}$$

Betweenness centrality measures the level of connectedness of an actor to those that would otherwise be disconnected. Actors with high BC measures are hypothesized to be acting as “gatekeepers” or “intermediaries” within a social network (ibid). Valentine (1995) posits that betweenness centrality measures how often an individual actor is located on the shortest path between other actors and sub-networks. Actors with a high degree of betweenness exhibit a relatively high level of independence as they experience higher flows of information and may also receive new information sooner than other actors. A higher betweenness centrality measure implies a greater level of control over information (ibid). Equation three contains the betweenness equation, where g_{ij} represents the number of ties linking *i* and *j* and $g_{ij}(p_k)$ is the number of these ties that contain individual *k*.

$$BetweennessCentrality = 2\sum_i \sum_j \frac{\frac{g_{ij}(p_k)}{g_{ij}}}{n2-3n+2} \qquad \text{Equation 3}$$

The eigenvector measure is an indicator of power within a social network. Eigenvector measures the centrality of the individual actor, weighted by the centrality measure of that particular actor's connections (Bonacich 1972). A high eigenvector rating implies relative power in a network is derived from the relative importance of an actor's connections, not the quantity of connections. Actors with a high eigenvector measure are regarded as powerful and influential actors within a social network (Ryan, 2008). An actor with a higher eigenvector ranking suggests greater diversity in sources of information (ibid).

The objective of this study is to identify, locate and categorize all actors related to pulse breeding R&D, to assess how they interact and to identify whether certain types of actors occupy positions of power and influence. Two methods were employed in this search. First, an internet search was conducted starting with known public pulse breeding institutions to search for institutions engaged in pulse R&D. This was augmented with emails, phone calls and interviews. The relationships identified between actors and institutions are formal, contractual, research or financially based.[3] The second method was a key word search through the ISI Web of Knowledge database to identify research and financial relationships between pulse breeders, funding agencies and institutions. The search was conducted using the following keywords, pulse crops, legumes, dry peas, chickpeas, lentils, faba beans, dry beans and lupins.

The social network analysis was undertaken using Organizational Risk Analyzer (ORA), a SNA software program developed by the Centre for Computational Analysis of Social and Organizational Systems (CASOS) at the Institute for Software Research at Carnegie Mellon University. The empirical results were imported into Microsoft Excel 2003 and analyzed using the statistical functions.

Individual organizations were evaluated as candidates for central actor functions by comparing their individual centrality scores against the average centrality score for each measure in each of the national sub-systems and in the global network. Only those institutions that had a centrality measure greater than one standard deviation higher than the mean of the source population were considered central actors. Thus, in each of tables that follow the number of stars indicates the number of standard deviations the individual measure of central tendency is above the mean for the entire population. Any institutions recording a centrality measure below this threshold are considered to not be undertaking those central functions.

5. Findings

This analysis offers insights into the network composition and institutional configuration of four interconnected but unique operational R&D networks. They range in size from 66 to 248 actors, have varying density (from .023 to .105) and involved a mix of individual key actors. All four networks share a single common feature—PGR-P3s provide structural integrity to each network. Of the 19 actors with measures one standard deviation or more above the mean of the three measures in the Export System, 13 (68%) are P3s, including the top ranked actor in each of the centrality rankings. (See table 5). One hundred percent of the central actors in the Developing System are P3s (9 of 9) (table 9). One P3 is ranked number one in all three categories in the EU System (table 7), but overall, P3s occur much less often as central actors (18%) in the EU. In the Global System (table 11), 20 out of 25 (80%) top ranked actors, again, are P3s. As characterized by the three SNA measures, P3s are the top ranked actor in each category in each of the four networks.

Table 4: The Four Pulse Innovation Networks

			Number of central actors based on centrality measures one standard deviation or more above the mean		
Network	***N***	***Density***	***Total Degree Centrality***	***Betweenness Centrality***	***Eigenvector Centrality***
Export System	66	.105	8	6	5
EU System	134	.040	10	2	10
Developing World	69	.055	3	2	2
Global System (aggregate)	248	.023	9	6	10

[3] There some limitations to the data. In Australia, some relations involving CSIRO and the Centre for Innovative Legume Research may not be included. In the EU we may have missed some research and funding relations within this network. The information for the Developing World System may have overlooked financial and research relations between selected donor and recipient countries and institutions.

In each of the four networks, P3s serve as the focal point for their respective R&D network. The Export System is distinguished by the prevalence of producer-funded and governed P3s that link the national systems of the United States, Canada and Australia together. The vulnerability assessment (in section 5.4 below) demonstrates that by removing two key P3s and one government center the 66 actor system fragments into an isolated Canadian network of 21 actors, an isolated and disconnected US system and a much reduced Export System centered on Australia. The EU System is characterized by a single intergovernmental P3, GLIP, which connects almost 40 different networks, sub-networks and isolates into a single R&D network of 134 actors. The Developing World System is centered on two key P3s, each centering a unique hub and spoke configured R&D network, which develops into a dual hub and spoke network.

5.1 The export system

This system consists of the major export countries of Canada, the USA and Australia along with the International Center for Agriculture Research in the Dry Areas (ICARDA) and International Crops Research Institute for the Semi-Arad Tropics (ICRISAT) and some individual research centers in France, India and South Africa. Institutionally, this system is composed of 17 P3s (26%), 22 universities (33%) and 27 government research centers (41%). There is a discernable absence of private firms. As indicated in table 5 the primary actors are the Crop Development Center/Saskatchewan Pulse Growers (CDC/SPG) partnership, the GRDC-Grains Research and Development Center, the Center for Legumes in a Mediterranean Area (CLIMA) and ICARDA—all four are P3s. As earlier noted, 13 of the 19 centrally ranked actors in this network are P3s. The network density is .105 (i.e. about 10% of all potential linkages are realized), the highest of all of the systems and subsystems investigated, which correlates with the relatively larger number of new varieties this system produces relative to the other systems.

With one notable exception all of the central actors in this system are P3s. The CDC/SPG is the top ranked actor according to the total degree and betweenness centrality rankings, suggesting this particular P3 is a highly connected gatekeeper controlling the flow of new information into the network and between sub-networks and isolates. Both measures suggest the CDC/SPG possesses a unique status with regards to independence and influence from and over the entire network. See table 5 below for the three centrality rankings. The GRDC and CLIMA have noteworthy total degree centrality measures indicating a higher than average level of intra-network activity. Five of the six top ranked eigenvector actors are Australian, implying the Australian pulse R&D network is uniquely positioned as a power broker within the Export System.

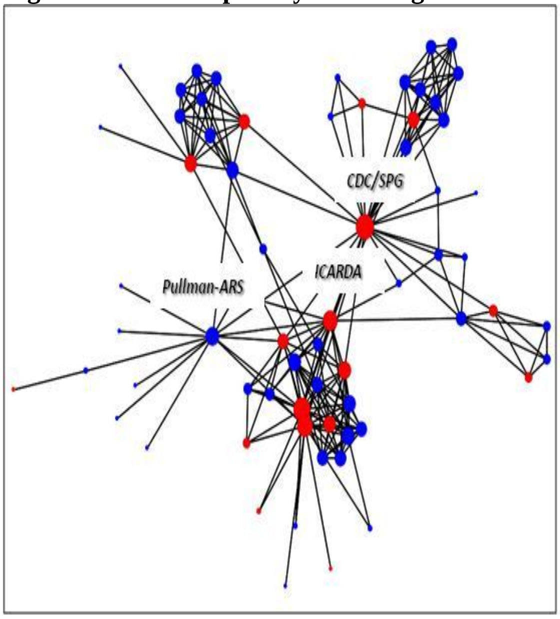
Table 5: Export System Actors & Centrality

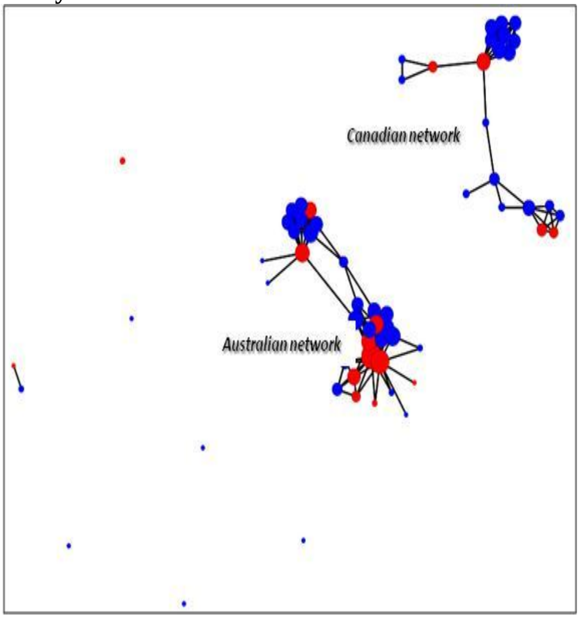
	Total Degree Centrality	Power (EC)	Influence (BC)
CDC/SPG	0.3692***	-	0.4754***
GRDC	0.3231**	1.000**	0.1353*
CLIMA	0.2923**	0.9049**	0.1305*
ICARDA	0.2462*	0.7317*	0.1171*
Pullman-ARS	0.2000*	-	0.2265**
PBA	0.1846*	0.7482*	-
DAFWA	0.1846*	0.7428*	-
CSIRO	0.1846*	-	-
MSU	-	-	0.1245*

* number of standard deviations greater than the mean
Source: Authors' calculations

The Export System has the highest level of intra-network connectedness as demonstrated by the comparative density analysis in table 5. Figure 2A, below, shows the Export Network with the P3s highlighted in red.

Figure 2A: The Export System   Figure 2B: Less 3 key actors





The sensitivity analysis contained in figure 2B, above, demonstrates how dependent the Export System is on a small group of actors. The removal of three key actors fragments this regional network into two national systems, one each in Canada and Australia, and a number of isolates, the fragments of the US system. The three critical actors are the CDC/SPG, ICARDA and the Pullman-ARS facility. Pullman-ARS is a US Government agricultural research center. Their removal has a detrimental effect on the composition of the network as highlighted in table 6. While CDC/SPG, ICARDA and Pullman-ARS represent less than 5% of the overall system, their deletion would causes a reduction in the physical structure of the network ranging from 14% to 97% depending on the function. As discussed earlier, innovation, the driver of economic growth, is derived from linking into the global pipelines and flows of knowledge. If this is the case, then the disintegration of the Export System into two national systems and a number of isolates would inhibit knowledge production, stifling economic growth in this sector.

Table 6: An estimate of the vulnerability of the Export System

	With CDC/SPG, Pullman-ARS and ICARDA	**Without CDC/SPG, Pullman-ARS and ICARDA**	**% effect of loss of 3 central actors**
# nodes	66	63	-4%
# links	454	354	-22%
Density	0.105	0.090	-14%
Network centralization	0. 272	0. 206	-24%
Betweenness	0. 456	0. 094	-79%
Closeness centralization	0. 437	0. 011	-97%
Fragmentation	1	10	+900%
Characteristic path	2.6765	1.880	-30%
Authors' calculations			

5.2 The EU system

The EU System is the largest of the three sub-systems with 134 actors. There are 27 P3s (20%), 40 government research centers (30%), 55 universities (41%) and 12 private sector actors (9%). This system is characterized by the critical role of a single P3, the Grain Legumes Integrated Project (GLIP), an intergovernmental P3 designed to boost EU pulse crop production. With the exception of GLIP, the EU system is characterized by the near absence of P3s as centrally ranked actors. In this system the predominant institutional type is the government agency. As noted in table 4, the EU System has the lowest density of the three regional networks with a measure of .040.

Table 7: EU System Actors & Centrality

	Intra-Network Connectivity (TDC)	Power (EC)	Influence (BC)
GLIP/FP6	0.5789********	1.000****	0.7112*********
INRA-HQ	0.2331***	-	0.1656**
CSIC	0.1654**	0.8243***	-
John Innes	0.1579*	-	-
IFAPA	0.1278*	0.7367**	-
GenXPro	0.1203*	0.7669**	-
Rennes INRA	0.1203*	0.8016***	-
CNRS	0.1128*	-	-
Frankfurt U	0.1128*	0.6821**	-

* number of standard deviations greater than the mean
Source: Authors' calculations

As indicated in table 7, based upon the three centrality rankings there is a single critical actor—GLIP. Interestingly, GLIP and the John Innes Center are the only two P3s that are centrally ranked. Apart from GenXPro, a private firm, the rest of the central functions are occupied by government agencies: INRA-HQ, INRA-Rennes, CSIC, IFAPA and CNRS. The EU System is further delineated by the dearth of influential actors according to the betweenness (BC) measurements. The only two organizations in this network with significant BC rankings are GLIP, and INRA-HQ, implying the existence of numerous relatively isolated and unconnected sub-networks and clusters within this regional system.

Figure 3A, below, depicts the EU System. The sensitivity analysis confirms the central position of GLIP and of the existence of a number of relatively unconnected sub-systems and isolates. Removing GLIP, one out of 134 actors, causes this system to fragment into a network of 94 actors and 38 isolates (Figure 3B).

Figure 3A: The Total EU System

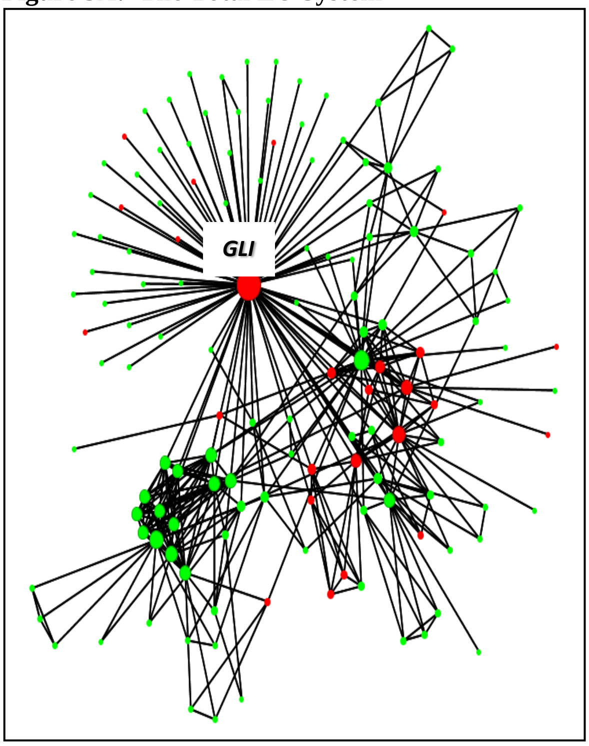
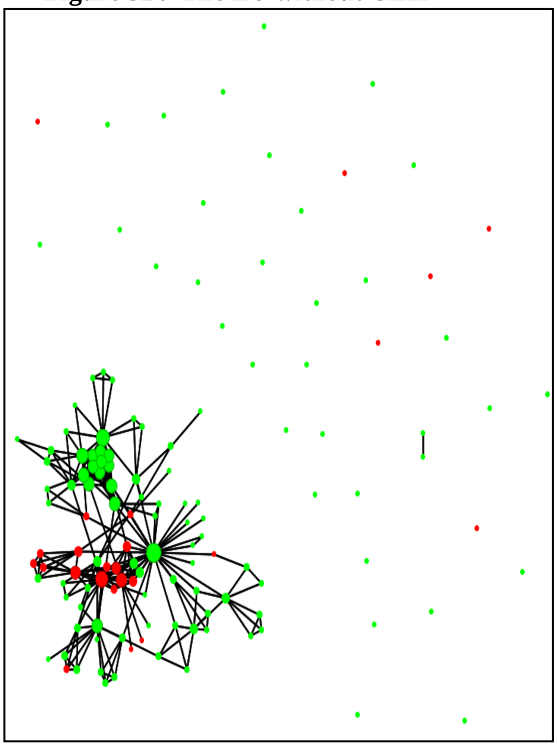


Figure 3B: The EU without GLIP



The removal of GLIP causes network density and the number of links to drop by more than 20%, while the structural coherence of the network, as determined by the three network measures, is reduced by between 60% and 90% (table 8). The placement of a large number of government research agencies in the centrality rankings along with the presence of GLIP, an intergovernmental P3, reflects the large number of relatively unconnected national pulse R&D systems in Europe and the Mediterranean basin. In this particular case, the sensitivity analysis is not an abstract exercise, as the funding for GLIP does not appear to have been renewed after 2008.

Table 8: An Estimate of the Vulnerability of the EU System

	With GLIP	Without GLIP	% effect of loss of GLIP
# nodes	134	133	-1%
# links	708	554	-22%
Density	0.040	0.031	-23%
Network centralization	0.547	0.199	-64%
Betweenness	0.705	0.226	-68%
Closeness centralization	0.601	0.011	-98%
Fragmentation	1	78	+7700%
Characteristic path	2.576	2.927	+14%
Authors' calculations			

5.3 *The developing-world system*

There are a total of 69 actors in the Developing World System, consisting of 10 P3s (14%), 41 government agencies (59%), 17 universities (25%) and one private actor (2%). This system is distinguishable by its unique dual hub and spoke configuration, as the Developing World System is created by existence of two developmental-oriented P3s, ICARDA and ICRISAT. As noted in table 4, the density of this network is .055, ranking in between the Export and EU Systems.

As demonstrated in table 9, P3s are the only institutional actors centrally placed in this network. ICARDA, ICRISAT and to a lesser degree CLAN, all P3s, are the only centrally ranked actors in this network. Based on all three measures, ICARDA is the most influential actor, being the most intra-connected and most powerful entity.

Table 9: Developing World System Actors & Centrality

	Intra-Network Connectivity (TDC)	Power (EC)	Influence (BC)
ICARDA	0.6912******	1.0000*****	0.7844*****
ICRISAT	0.4559***	0.7493****	0.3627***
CLAN	0.2353*	0.4979**	--
* number of standard deviations greater than the mean Source: Authors' calculations			

Essentially, these two P3s connect the national agriculture research systems of various developing world counties into a regional sub-system (Figure 4A). As shown in figure 4B the sensitivity analysis substantiates the important role of the central actors—the removal of ICARDA, ICRISAT and CLAN causes the network to disintegrate into 33 isolates and nine mini-networks of at least two actors each, in place of the one network.

Figure 4A: The TotalDeveloping World System

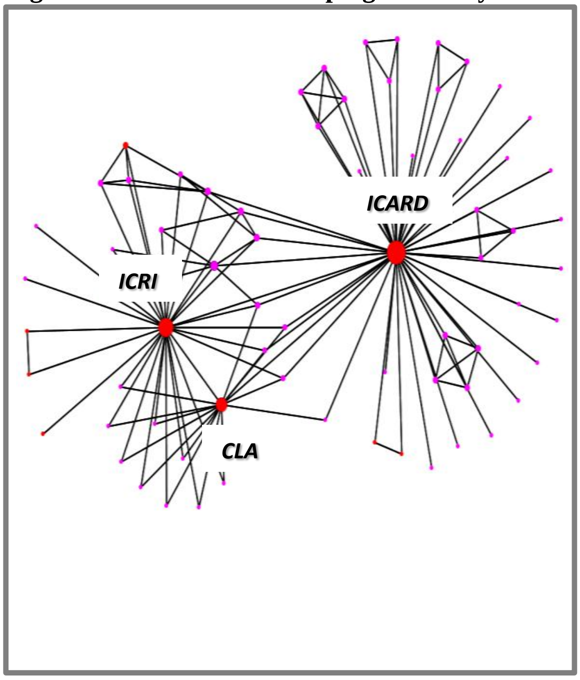


Figure 4B: Without the three core P3s

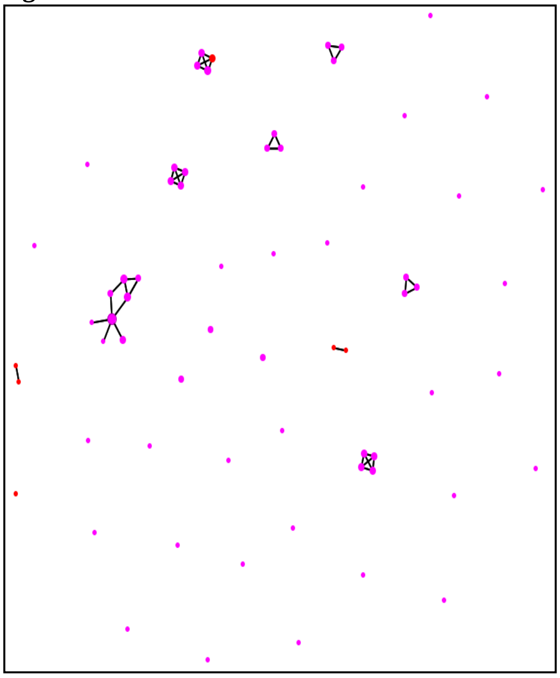


Table 10 confirms the visual analysis, as network composition is reduced by 67% to 99%, depending on the measurement.

Table 10: An Estimate of the Vulnerability of the Developing World System			
	With ICARDA, ICRISAT and CLAN	**Without ICARDA, ICRISAT and CLAN**	**% effect of loss of 3 central actors**
# nodes	69	66	-4%
# links	258	76	-72%
Density	0.055	0.018	-67%
Network centralization	0.655	0.061	-91%
Betweenness	0.776	0.074	-91%
Closeness centralization	0.650	0.003	-99%
Fragmentation	1	75	+7400%
Characteristic path	2.272	1.439	-54%
Authors' calculations			

5.4 The Global System

As previously discussed, there are 248 actors in the Global System. This includes 45 P3s (17%), 107 government research agencies (43%), 83 universities (34%) and 13 private entities (6%). The Global System is displayed in figure 5 below. Four critical P3s—CDC/SPG, ICARDA, ICRISAT and GLIP—are labelled on the Global System. The network density of .023 (table 4), is the lowest of the four networks, suggesting that the most important connections are primarily within the three regional networks, with exchanges of technology and information between key actors facilitated and mediated by the gatekeepers between the networks. The core P3s are highlighted in red for ease of reference.

GLIP, ICARDA, CDC/SPG and ICRISAT, all P3s, and INRA, a French government agency with extensive networking functions, are the top actors in each of the three categories of centrality for the global system. In the entire Global System, 20 out of 25 top centrally ranked actors are P3s, suggesting their critical role in providing linkages between dissimilar institutions and networks.

Table 11: Global System Actors & Centrality			
	Intra-Network Connectivity (TDC)	**Power (EC)**	**Influence (BC)**
GLIP	0.2996********	0.9387*****	0.3853*********
ICARDA	0.2591******	1.0000*****	0.3247*******
ICRISAT	0.1579****	0.5496**	0.1396***
INRA HQ	0.1579****	0.8033****	0.1547***
CDC/SPG	0.1336***	0.8641****	0.2249*****
John Innes	0.1174**	0.6726***	-
GRDC	0.0850*	0.6230***	-
CLIMA	0.0810*	0.5791**	-
CSIRO	0.0810*	0.7747****	-
* number of standard deviations greater than the mean Source: Authors’ calculations			

As before, we undertook a sensitivity analysis to test the role key P3s occupy. As demonstrated in figure 6, removing four core P3s—ICARDA, ICRISAT, CDC/SPG and GLIP—causes a disproportionate loss of network coherence. As noted in table 12, removing these four P3s (about 2% of all actors) causes network impairment ranging from 25% to 98% depending on the measurement. Interestingly, the removal of these 4 P3s isolates the entire Canadian system and part of the US network, analogous to the results of the tinkering in the Export Sub-system. In particular, this analysis highlights the importance of the CDC/SPG as both a national and intercontinental gatekeeper. Without these four key players, the system fragments into 60 components reducing the size of the Global System to 159 linked actors, 21 actors in the isolated Canadian system, four mini-networks of two or more actors and over 50 isolates.

Table 12: An Estimate of the Vulnerability of the Developing World System			
	With ICARDA, ICRISAT, CDC/SPG and GLIP	**Without ICARDA, ICRISAT, CDC/SPG and GLIP**	**% effect of loss of 4 central actors**
# nodes	248	244	-2%
# links	1392	980	-30%
Density	0.023	0.017	-26%
Network centralization	0. 279	0.133	-52%
Betweenness	0.387	0.162	-58%
Closeness centralization	0.350	0.005	-99%
Fragmentation	1	60	+5900%
Characteristic path length	3.006	4.203	+40%
Authors’ calculations			

6. Contributions and implications

As the analysis demonstrates, the P3 is the organization that has demonstrated through practice that it is best equipped to link local and national systems of pulse R&D into three regionalized networks that form a global pulse R&D system. While P3s are at the centre, there is no single model of P3.

The producer-governed P3 is the key institution in the Export System. The three Australian actors—GRDC, CLIMA and PBA—all possess the highest eigenvector measures, suggesting the Australian pulse R&D network is tightly integrated with the global system. Canada’s core P3, the CDC/SPG, another producer-led consortium, completes the core of the export system. Producer led systems are not immune to budgetary pressures, but they tend to be more resilient in the face of adversity, often striking unconventional bargains to maintain their operations in tough times. In the US Pullman-ARS, a government actor, is a critical gatekeeper in the Export System, linking the US to the global system. While it has a somewhat limited role in the Global System, it remains important for US producers. Given the fiscal situation in the US, the long-term viability of this government funding is surely under review.

In the EU System, GLIP, an intergovernmental P3 that has ceased operations, is the one actor that has provided structural integrity and linked the Community-wide R&D network. Given the vulnerability of government-led and funded projects in this time of fiscal constraint, the EU strategy poses significant risks. If theory is correct regarding the dependence of economic innovation on capitalizing on the global flows of knowledge, the apparent demise of GLIP threatens to isolate the EU from the global R&D community. EU producers would then have two choices: they could depend on narrow, often uncompetitive national research programs for new varieties or they could seek to purchase new germplasm on open markets (often at a higher price than the underlying development costs).

The Developing World System is characterized by a hub and spoke system centered on two highly-connected international developmental P3s, ICARDA and ICRISAT. These international organizations provide vital intra-and inter-network linkages between the various national agricultural systems. The challenge they face is that they depend on a wide range of state and charitable sources of funds. ICARDA reports 39 sponsors in 2008, the majority nation states or agencies largely funded by nation states and ICRISAT reports 24 core donors (all state or state dependent organizations) and a long list of partnerships and projects funded directly by those donors. While any fiscal tightening might take some time to work its way into these institutions, it is likely they will feel constraints. Given their dependence on government support, they may have difficulty backfilling any cuts, thereby threatening their continued role as central actors in the Developing World part of this industry.

Looking at the system globally, four key P3s—CDC/SPG, GLIP, ICARDA and ICRISAT—representing the three types of P3—producer-led, intergovernmental and international developmental—provide the linkages and structural integrity for the Global System of 248 actors, suggesting that no single model is sufficient for successful R&D collaboration. Rather, a mix of institutions with P3-like attributes may be required to realize effective operations.

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Appendix A: Institutional coding			
Actor	**Location**	**Institution Type**	**Network**
GRDC	Australia	P3	Export
PBA	Australia	P3	Export
SARDI	Australia	Government	Export
VDPI	Australia	Government	Export
NSWDPI	Australia	Government	Export
QDPIF	Australia	Government	Export
DAFWA	Australia	Government	Export
ICARDA	CGIAR	P3	Global
ICRISAT	CGIAR	P3	Global
CLIMA	Australia	P3	Global
ACIAR	Australia	Government	Export
COGGO	Australia	P3	Export
CDC/SPG	Canada	P3	Global
Pullman-ARS	USA	Government	Export
CSIRO	Australia	Government	Global
U of Adelaide	Australia	University	Export
NPBP	Australia	P3	Export
Muresk Inst.	Australia	University	Export
NDSU	USA	University	Export
GCI-S Africa	S Africa	Government	Export
MSU	USA	University	Export
Prosser-ARS	USA	Government	Export
U of Wis	USA	University	Global
CIAT	CGIAR	P3	Global
CSU	USA	University	Export
U of Idaho	USA	University	Export
U of Guelph	Canada	University	Export
NRC	Canada	Government	Export
AAFC-Saskatoon	Canada	Government	Export
AAFC-Morden	Canada	Government	Export
AAFC-Lacombe	Canada	Government	Export
IH AAFC	Canada	Government	Export
IOA	Australia	Government	Export
WAHRI	Australia	P3	Export
FFICRC	Australia	P3	Export
Tasmanian Inst Agr Res	Australia	Government	Export
Punjab Agr Univ	India	University	Export
UWA	Australia	University	Export
U of NFLD	Canada	University	Export
Guelph AAFC	Canada	Government	Export
MII AAFC	Canada	P3	Export
SC AAFC	Canada	Government	Export
Purdue	USA	University	Export
New Mexico	USA	University	Export
Montana State Univ	USA	University	Export
Scott AAFC	Canada	Government	Export
Univ Manitoba	Canada	University	Export
Univ Alberta	Canada	University	Export
AAFRD	Canada	Government	Export
ACIDF	Canada	P3	Export
APGC	Canada	P3	Export
WGRF	Canada	P3	Export
Northern Pulse Growers	USA	P3	Export

CILR	Australia	P3	Export
John Innes	UK	P3	Global
NC State	USA	University	Export
Queensland U	Australia	University	Export
ANU	Australia	University	Export
U of Newcastle	Australia	University	Export
U of Melbourne	Australia	University	Export
KDNARI	Japan	Government	Export
USDA-STPaul	USA	Government	Global
CLAN	Asia	P3	Developing
FIA	Austria	Government	Developing
AGERI	Egypt	Government	Developing
MTT	Finland	Government	Developing
DSMZ	Germany	Private	Developing
University of Frankfurt	Germany	University	Global
University of Hannover	Germany	University	Global
CRA	Italy	Government	Developing
UC Davis	USA	University	Global
TIGR	USA	Private	Global
IFPRI	Spain	P3	Developing
Egypt NARS	Egypt	Government	Developing
Tunisia NARS	Tunisia	Government	Developing
Ethiopia NARS	Ethiopia	Government	Developing
BARC	Bangledash	Government	Developing
ICAR	India	Government	Developing
PARC	Pakistan	Government	Developing
Morocco NARS	Morocco	Government	Developing
AREEO	Iran	Government	Developing
Turkey NARS	Turkey	Government	Developing
Aleppo University, Syria	Syria	University	Developing
BAU	Bangledash	University	Developing
Rajshahi University, Bangladesh	Bangledash	University	Developing
Alemaya University, Ethiopia	Ethiopia	University	Developing
GAU	Georgia	University	Developing
LARI	Lebanon	Government	Developing
CRIDA	India	Government	Developing
NCPGR	India	Government	Developing
CAAS	China	Government	Developing
CRIFC	Indonesia	Government	Developing
DAR	Myanmar	Government	Developing
NARC	Nepal	Government	Developing
PCARRD	Philippines	Government	Developing
SLDOA	Sri Lanka	Government	Developing
DOAT	Thailand	Government	Developing
MARDV	Vietnam	Government	Developing
MARY	Yemen	Government	Developing
NCPGR India	India	Government	Developing
NRCPB	India	Government	Developing
IARI	India	Government	Developing
SVPUAT	India	University	Developing
TLP	CGIAR	P3	Developing
EIAR	Ethiopia	Government	Developing
LZARDI	CGIAR	P3	Developing
Gates Foundation	USA	P3	Developing
IIPR	India	Government	Developing

PBI-CA Univ Germany	Germany	University	Developing
BMZ	Germany	Government	Developing
KVL	Denmark	University	Developing
PRC	Bangledash	Government	Developing
BARI	Bangledash	Government	Developing
U of Helsinki	Finland	University	Developing
BAZ	Germany	Government	Developing
U of Wolverhampton	UK	University	Developing
U of Gottingen	Germany	University	Developing
CSIC	Spain	Government	Global
IFAPA	Spain	Government	Global
NYRC	Israel	Government	Developing
U of Greenwich	UK	University	Developing
Wageningen University	Netherlands	University	Global
IAMZ	Spain	Government	Developing
ISA	Spain	Government	Developing
UC-Riverside	USA	University	Developing
WARDA	CGIAR	P3	Developing
IRRI	CGIAR	P3	Developing
INRA HQ	France	Government	Global
GLIB/FP6/FP7	EU	P3	EU
INIFAP	Mexico	Government	EU
GenXPro	Germany	Private	EU
Svetošimunska 25	Croatia	Government	EU
Universita di Pisa	Italy	University	EU
U.P.M.	Spain	University	EU
C.B.G.P	Spain	Government	EU
CNRS	France	Government	EU
Bielefeld University	Germany	University	EU
AEP	France	P3	EU
MPI	Germany	University	EU
GCNRG	France	Government	EU
TWTSInT	UK	P3	EU
JWGU	Germany	University	EU
University of Dundee at SCRI	UK	University	EU
BRC	Hungary	University	EU
Animal Sciences Group	Netherlands	University	EU
University of Córdoba	Spain	University	EU
MIPS	Germany	University	EU
Schothorst Feed Research	Netherlands	Private	EU
UAAR	Denmark	University	EU
SWRSAA	Switzerland	Government	EU
FIB	Belgium	Government	EU
IPK	Germany	Government	EU
RISØ	Denmark	Government	EU
IVV, Fraunhofer Institute	Germany	P3	EU
NARCN	Norway	Private	EU
ESA	France	University	EU
PRI-NETH	Netherlands	P3	EU
ILB	Sweden	P3	EU
PAS	Poland	Government	EU
University of Leon	Spain	University	EU
CLS	UK	Government	EU
University of Sevilla	Spain	University	EU
IBMC	Portugal	University	EU

CEREOPA	France	University	EU
NIAB	UK	P3	EU
UPN-SP	Spain	University	EU
CESFAC	Spain	University	EU
CZU	Czech Republic	University	EU
University of Reading	UK	University	EU
IGER	UK	University	EU
UNIP	France	P3	EU
PBAI	Poland	University	EU
ARO	Israel	Government	EU
ABIO	Bulgaria	Government	EU
AEL	Spain	Government	EU
University of York	UK	University	EU
Murdoch University	Australia	University	EU
IG-ABC	Hungary	Government	EU
IRM	Italy	Government	EU
University of Ghent	Belgium	University	EU
GL-TTP	France	P3	EU
ADAS	UK	Private	EU
ARRIAM	Russia	Government	EU
FAKS	Egypt	University	EU
FAN	Gaza/West Bank	University	EU
IAV	Morocco	University	EU
INRAT	Tunisia	University	EU
EMBRAPA	Brazil	Government	EU
UCB	Brazil	University	EU
SIPPE	China	Government	EU
University of the Witwatersrand	S. Africa	University	EU
ITQB	Portugal	Government	EU
PCGIN	UK	P3	EU
PGRO	UK	P3	EU
CIMMYT	CGIAR	P3	EU
APPO	Belgium	P3	EU
UFOP	Germany	P3	EU
EC	EU	Government	EU
IITA	CGIAR	P3	EU
DEFRA	UK	Government	EU
LESP	France	University	EU
UFPE	Spain	University	EU
IBRC	Japan	Government	EU
FST U of Tunis	Tunisia	Government	EU
Université de Nantes	Italy	University	EU
LM Univ Munchen	Germany	University	EU
U of MN	USA	University	EU
LSPPPBV	France	Government	EU
U of Oxford	UK	University	EU
PPRI	S. Africa	Government	EU
USD	Algeria	University	EU
Université d’Abobo-Adjamé	Ivory Coast	University	EU
Université de Picardie	France	University	EU
INP-ENSAT	France	Government	EU
Limagrain	France	Private	EU
Wherry & Sons Ltd	UK	Private	EU
SR Noble	USA	P3	EU
IPG-BZFAR	Hungary	P3	EU

Stanford University	USA	University	EU
Nancy University	France	University	EU
NKMU	Taiwan	University	EU
University of Georgia	USA	University	EU
CBBC	Tunisia	Government	EU
NPZ	Germany	Private	EU
BioPlante	France	P3	EU
Serasem	France	P3	EU
Agrovegetal SA	Spain	Private	EU
Array-On GmbH	Germany	Private	EU
ITACyL	Spain	Government	EU
Saatzucht Steinach GmbH	Germany	Private	EU
U of Valladolid	Spain	University	EU
Angers INRA	France	Government	EU
Dijon INRA	France	Government	EU
Montpellier INRA	France	Government	EU
Nantes INRA	France	Government	EU
Poitou Charentes INRA	France	Government	EU
Rennes INRA	France	Government	EU
Toulouse INRA	France	Government	EU
Versailles-Grignon INRA	France	Government	Global
UMR-LEG Bretenieres INRA	France	Government	EU
Lusignan INRA	France	Government	EU
Mauguio INRA	France	Government	EU
Castanet-Tolosan INRA	France	Government	EU
ILM	France	Government	EU
Agrovegetal SA	Spain	Private	EU
Array-On GmbH	Germany	Private	EU