Public Agricultural Research, Political Economy, and Climate Change: A Literature Review

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Abstract

Impacted by both economic and political forces, agricultural research serves as a critical approach to mitigating the adverse effects of climate change. Focusing on public agricultural research in the United States, this paper provides a literature review on research and development from the perspectives of market environment and political economy. It also examines the current assessment of agricultural research effectiveness in addressing the challenges of climate change. A bibliometric analysis is conducted to appreciate the knowledge dynamics in the nexus of agricultural research, political economy, and climate change. Future research directions related to public agricultural research are discussed.

Keywords: Agricultural Research, Bibliometric analysis, Climate Change, Political Economy

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Agriculture over the course of human history has been constantly reshaped by technological innovations (Mazoyer and Roudart, 2006). This impact of innovations on agriculture manifested itself in the tremendous increase in agricultural productivity over the past one hundred years (Pardey and Alston, 2021). Facing current grand challenges such as climate change and global food security, societies view agricultural innovation as one critical means to respond (Smit and Skinner, 2002). Unlike many ancient innovations or discoveries that were often results of random events, modern innovations are generally the products of systematically organized research endeavors (Lin 1995). Public funds have been a critical component in the support of agricultural research in the United States. However, in the past two decades, they showed a concerning downward trend (Nelson and Fuglie, 2022). Public policies, as outcomes of pressures from various interest groups in a society, play a critical role in affecting these organized research endeavors. Henry Wallace, former Secretary of Agriculture in the United States, once noted, "Scientific understanding is our joy. Economic and political understanding is our duty" (Wallace, 1961). Focusing on US agriculture, in this paper we provide a review of the literature on public agricultural research from the perspectives of market environment and political economy. We then investigate literature on the effectiveness of current agricultural innovations in addressing the challenges of climate change, and discuss potential future research directions in the realm of agricultural innovation.

Quite a few review articles have investigated various aspects of agricultural research and innovation. For instance, Clancy and Moschini (2013) discuss the economics of three innovation incentive mechanisms, namely, patent, prize, and research contract. Focusing on biotechnology in agriculture, Herring and Paarlberg (2016) offer a comprehensive political economy overview of reasons why funding for public agricultural research had decreased over the past few decades. Alston and Pardey (2021) provide a comprehensive review of the economics the economic returns of agricultural research and development (R&D), as well as the determinants and distribution implications of agricultural R&D. Smith, Wesseler, and Zilberman (2021) review the literature on the political economy of regulations imposed on genetically modified crops and gene-editing technologies used on crops. Differing from the existing reviewer articles, the present paper aims to understand public agricultural research through the lens of political economy, and to evaluate whether the public agricultural research would meet the demand from responding to climate change by incorporating most recent findings in the literature.

We first briefly summarize the institutional background of public agricultural research in the United States, including its history and current status. Then, to prepare for discussions about public agricultural research from the perspectives of market environment and political economy, we provide a brief review of two major economic theories on innovation (i.e., induced innovation and directed innovation) and some basic political economic theories (e.g., median voter theorem, capture theory, pressure group theory, and cooperative games between government and interest groups). We then discuss recent literature that considers the connection between innovation and political influences. After that, the paper proceeds with reviewing the literature and discussing research gaps in the realms of a) explaining agricultural R&D expenditures, b) understanding the contribution of agricultural experiment stations and land-grant universities to agricultural innovation, and c) addressing global challenges by using agricultural innovations.

Finally, we augment the literature review by conducting a bibliometric analysis of the relevant literature discussed in the paper, and share some insights obtained from such an analysis. In today's research landscape, an expansive tide of scholarly output constantly flows, underscoring the significance of comprehending knowledge dynamics. By quantitatively analyzing patterns of publications, citations, keyword co-occurrence, collaborations, and other bibliographic data, bibliometric analysis can be a useful tool that provides valuable insights into the landscape of scholarly research (Van Eck and Waltman 2017), allowing researchers to identify emerging research trends and topics within a specific field or discipline (Ellegaard and Wallin 2015, Rejeb et al., 2022, Ulucak et al. 2021). It can serve as a compass for understanding the dynamic currents of ideas and knowledge flow, revealing influential works and mapping the ripples of research impact across disciplines, regions, and timeframes. Based on bibliometric analysis, researchers can appreciate how ideas and knowledge flow, identify influential works and track the impact of research in specific areas since it helps trace the diffusion and dissemination of scientific knowledge across disciplines, regions, and over time (Cobo et al. 2011a, Donthu et al. 2021). Building upon this foundation, our study also conducts a bibliometric analysis centered around the political economy of agricultural research in the context of climate change. To the best of our knowledge, this paper is among the earliest efforts to conduct bibliometric analysis on the literature of agricultural public research.

BACKGROUND: US PUBLIC AGRICULTURAL RESEARCH

Enacted in 1862 to establish the U.S. Department of Agriculture and land-grant colleges, the Morill Act was the result of nearly two decades of political movements in various states calling for agricultural instruction and research. In 1887, to meet the research demand from local farmers across the country, the Hatch Act was passed into law to establish an agricultural experiment station system. In 1914, about a quarter century after the Hatch Act, Cooperative Extension Service was established in all states to bridge agricultural research and farmers.

Nowadays, Land-grant colleges, experiment stations, and the USDA are still the backbone of public agricultural research (Perry 2023). However, in the past two decades, funding for public agricultural research declined about one third in the United States (from $6 billion to $4 billion), while funding in other major agricultural countries or regions such as European Union, China, India, and Brazil was continuously increasing (Nelson and Fuglie, 2022). Notably, in the past decade the public funding for agricultural research in the United States was about half of that in China. If the declining trend continues, then the United States may well be surpassed by India and Brazil in terms of public agricultural research funding in the near future, ranking only the fifth in supporting agricultural research.

Agricultural R&D expenditure is a major diver for agricultural innovation. Not surprisingly, a major branch of agricultural innovation literature concerns agricultural R&D expenditure, with two relevant lines of explorations at the center: the return rate of agricultural R&D and the determinants of agricultural R&D expenditure magnitude. Many studies have quantified the return rate of agricultural R&D expenditure. Although the specific estimates differ due to differences in methodologies and technologies in question, there is a consensus that the return rate to R&D expenditure is quite high (see Alston and Pardey (2021) for a comprehensive review). For instance, Alston and Pardey (2021) document that the average of internal rate of returns of agricultural R&D in the United States is 54.6 (see their Table 5). At such a high return rate, an efficient market or government would increase investment in agricultural R&D, and eventually bring down the return rate. However, this is not happening in reality. Instead, US public agricultural R&D expenditure decreased by about 1/3 in the past two decades (Nelson and Fuglie 2022). Why is this happening?

In his Agricultural and Applied Economics Association (AAEA) Fellow address celebrating the 100th anniversary of the Hatch Act, Rasmussen (1987) offered an intriguing discussion about the history of agricultural experiment station research in its first 100 years, from which we can clearly see the roles of various interest groups in shaping the directions of research conducted on agricultural experiment stations. Rasmussen (1987) also proposed future directions for experiment station research, which are still quite relevant 36 years later. Unfortunately, in almost four decades since its publication, Rasmussen (1987) had only been cited by once as of July 2023 based on the Web of Science, partially indicating a lack of attention to research about experiment station. As Rasmussen (1987) pointed out, "The system [experiment stations] has worked well for its first hundred years. It is our duty to see that it continues to work well for the next one hundred years." The question is, "How?" Understanding the political economy of public agricultural research may be an important component of the answer. Before we dive into this issue, we first briefly discuss several key models in innovation economics and political economy.

EARLY LITERATURE: INNOVATION ECONOMICS AND POLITICAL ECONOMY

Innovation has long been a focus in economic literature, and related research can be largely divided into two realms. The first realm concerns the overall *rate* of innovation, studying the drivers of technical change speed. The endogenous growth literature (e.g., Romer 1990; Aghion and Howitt 1992) and the literature of R&D investment largely fall into this realm. The other realm focuses on the *directions* of technical changes, investigating why and to what extent innovations are increasing productivity of one factor instead of another. Induced innovation theory and directed innovation theory are two major theories in this realm. In this section we briefly review the literature related to the direction of technical changes because it attracted much attention of agricultural economists.[1] At the end of this section we outline some basic models of political economy.

Induced innovation theory

The induced innovation theory claims that, as famously stated by Hicks (1932, pp. 124-125), "a change in the relative prices of the factors of production is itself a spur to invention, and to invention of a particular kind—directed to economizing the use of a factor which has become relatively expensive." Early theoretical works related to the induced innovation theory aimed to formalize the hypothesis and to establish a microeconomic foundation for it (e.g., Habakkuk 1962; Kennedy 1964; Samuelson 1965; Ahmad 1966; Binswanger 1974a,b; and Funk 2002). Particularly, this literature introduced innovation possibilities, either via an Innovation Possibility Frontier as in Kennedy (1964) or via an innovation possibility curve as in Ahmad (1966), so that firms could choose the directions of innovations. Binswanger (1974a) explicitly considered innovation costs and innovators' profit maximization. Funk (2002) developed an induced innovation theoretical framework considering rational firms and perfect competition.

Empirical studies on testing the induced innovation theory have not reached a consensus, even within the field of agricultural innovation. Hayami and Ruttan (1970) find supporting evidence for the theory based on data for US and Japanese agriculture. The authors illustrate that the abundant arable land in the United States over 1880-1960 made US agriculture relatively labor-constrained, whereas the limited supply of land in Japan made Japanese agriculture over

[1] A review of the endogenous growth theory and rate of innovation is out of scope of this paper. We refer readers to Cecere (2015) and Akcigit and Nicholas (2019) for comprehensive reviews of these topics.

the same period land-constrained. They argue that these features in factor ratios in the two countries determined that labor-augmenting technologies (e.g., tractors) occurred in the United States while the land-augmenting technologies (e.g., fertilizers and biotechnologies) occurred in Japan in early 20th century. However, based on state and regional agricultural data in the United States, Olmstead and Rhode (1993) argue that US agricultural history does not lend support to the induced innovation theory. They point out that changes in factor uses in US agriculture should be explained by the Westward Movement and biological investments. Using the case of wheat, Olmstead and Rhode (2002) show that biotechnology innovations, contradicting the findings in Hayami and Ruttan (1970), were actually pursued actively and contributed to US wheat yield significantly in the 19th and early 20th century. Cowan et al. (2014) criticize that early empirical explorations of the induced innovation theory ignored the marginal cost of innovation and therefore might have reached biased conclusions. By focusing on US public agricultural research and using state-level panel data for input prices and agricultural R&D expenditure, Cowan et al. (2104) find that an increase in relative price between fertilizer and energy is associated with increased public R&D expenditure ratio of fertilizer to energy, supporting the induced innovation theory. The same conclusion holds for three additional input pairings: energy-land, fertilizer-land, and fertilizer-labor. However, they do not find supporting evidence for labor/land and labor/energy input pairings.

The induced innovation hypothesis has received extensive criticisms since it was proposed. Salter (1960) argue that firms are indifferent among inputs when seeking to reduce costs unless it is easier to reduce costs from one factor than from others. In other words, for a profit-maximizing firm, one dollar of cost reduction from labor is as good as one dollar of cost reduction from capital if the two reductions have the same impact on revenue. Moreover, because in equilibrium factor prices equal marginal products of factors, it is not meaningful to claim that one factor is “more expensive” than another. Even though considerable efforts had been devoted to laying a microeconomic foundation for the induced innovation theory as described above, the hypothesis is still been criticized as lacking microeconomic foundation in various aspects. For instance, Nordhaus (1973) argue that in induced innovation theory innovation activities were not explicitly modeled. Although some later studies, such as Binswanger (1974) and Funk (2002), addressed some of these criticisms, induced innovation hypothesis had attracted little attention from the endogenous growth literature in the past three decades.

Directed innovation theory

Rooting his analysis in the endogenous technical change literature, Acemoglu (2002) shows that the relative economic incentive to innovate on two production input factors can be decomposed into two components. One is price effect (measured by relative factor price) that directs innovations toward factors that are relatively scarcer and thus more expensive. The other is market size effect (measured by relative factor quantity) that directs innovations toward the more abundant factor. The overall direction of technical change depends on which of the two effects dominates. If the price effect dominates the market size effect, then an exogenous decrease in a factor will increase its price and encourage innovations saving this factor, which is consistent with the prediction of the induced innovation theory. On the other hand, if the market size effect dominates the price effect, then such an exogenous decrease in the supply of one factor will encourage innovations toward the now relatively abundant factor, which contradicts the prediction of the induced innovation theory. Acemoglu (2002) finds that when two factors are substitutes, then the market size effect will dominate the price effect, whereas when two factors are complements, then the opposite is true. The intuition is that when two production factors are complements, an increase in the supply of one factor will decrease its own price but will increase the demand and thus price of the other factor, causing the relative price between these two factors to change significantly. As a result, the price effect dominates. On the other hand, if the two factors are substitutes, then an increase in one factor will decrease its own price and the price of the other factor as well. In this case, the relative price of the two factors does not change much, and therefore the market size effect dominates, encouring innovations toward the increased factor. Acemoglu (2002) shows that if the elasticity of substitution between factors is large enough, then in the long-run the factor price can be increasing in factor quantity due to the increased innovations augmenting this factor, termed "strong induced-bias hypothesis."

Hanlon (2015) shows empirical evidence supporting the directed innovation theory and the "strong induced-bias hypothesis" in the context of British cotton textile industry around the US Civil War period (1861-1865). The breakout of the U.S. Civil War significantly reduced the supply of US cotton to the British cotton textile industry, forcing the industry to substitute US cotton with lower quality India cotton. Hanlon (2015) shows that during 1861-1865 innovations that augmented India cotton increased dramatically, and the technical advances drove the relative price of Indian cotton over US cotton back to the pre-war level even the relative supply of Indian cotton increased significantly due to the US Civil War.

The literature discussed above focuses on the economic forces that determine the directions of technical changes. However, the political environment, wherein economic agents are located, can have significant impact on the directions of technical change. For instance, consumer groups may create significant political pressure onto policymakers to restrict land-augmenting biotech innovations that might impose health or environmental risks. In the remaining part of this section we briefly discuss some of the early political economy theories.

Political economy theories

Among many political economy theories (see Caporaso and Levine 1992), one strand of literature that focuses on the interaction between interest groups has been applied widely in agricultural economics to explain agricultural innovation (e.g., Graff et al., 2009; Herring and Paarlberg, 2016). Becker (1983) postulates an interest group competition model, arguing that the population can be divided into different interest groups and each interest group imposes political pressure on policymakers to influence policy outcomes (e.g., taxes or subsidies). Interest groups compete with each other to maximize their net incomes considering the benefits and costs of generating political pressure. Becker (1983) shows that it is the relative efficiency of generating political pressure matters the most for the competition outcome. He also suggests that smaller interest groups are typically more efficient in generating political pressure due to the free-rider problem of larger interest groups. Developed by Nash (1950, 1951, 1953) and Harsanyi (1962a,b, 1963), Nash bargaining game is another useful tool to analyze the interaction between political interest groups. We refer readers to Rausser et al. (2011, chapters 2 and 3) for a comprehensive review of this approach. The framework shows that under some general assumptions, the optimal solution of bargaining can be obtained by solving a straightforward optimization problem.

Quite different from the interest group competition or bargaining model, a conceptual framework developed by Akcigit et al. (2023) focuses on the impact of collusion between firms and political power on firms' innovation incentive. It shows that leading firms are more likely to form political connection and less likely to innovate. Moreover, when firm entrance and exit are considered, the possibility of political connection will hinder the entrance of new firms and prolong the life of leading firms. The authors conclude that political connection reduce innovation and industry dynamism in the long-run. Akcigit et al. (2023) further use universal micro-level data for Italian firms and politicians to test their theoretical findings and obtain supportive evidence. They conjecture that the mechanism that they discover may also apply to the United States when explaining the declining innovation dynamism and productivity. This innovation dynamism issue (see more in Akcigit and Ates 2021, 2023) might be able to explain why agricultural productivity growth had slowed down in the past three decades. Therefore, examining innovation dynamism of private agricultural firms and public research entities may be an interesting direction for future research regarding agricultural innovation and productivity growth.

Focusing on US agriculture, in the next two sections we discuss public agricultural research (e.g., its research support and entities) from a perspective of political economy in the context of climate change facing agriculture.

PUBLIC AGRICULTURAL RESEARCH AND POLITICAL ECONOMY

Many studies have adopted political economic models to explain the determinants of agricultural R&D expenditure.[2] Early studies, such as Guttman (1978), Huffman and Miranowski (1981), as well as Rose-Ackerman and Evenson (1985), show that research expenditure in a state is determined by the configuration of farms in the state, the importance of farming in the state, as well as the availability of state-level and federal-level funding. Huffman and Just (1999a,b)

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[2] In addition to studies quantifying the determinants of public research funding or the rate of returns of such funding (e.g., Huffman and Miranowski 1981; Jin et al. 2016), several studies focused on the fund allocation mechanism and management of public research, and their impact on research productivity (e.g., Huffman and Just, 1994, 1999a, 2000; Fuglie et al. 1996).

found that competitive grants were the most efficient mechanism for fund allocation, but a significant share of the research budget was allocated according to formulas to obtain political support from all states. They also argued that commodities grown in multiple states (grain, for example) would get much more federal support than specialty crops grown in few states. Finally, they found that commodities that commanded a higher share of their state's GDP will receive more political support to obtain government support funds.

By developing a partial-equilibrium political economic model, de Gorter and Zilberman (1990) show that if the commodity market is closed and competitive, and if the commodity demand is inelastic, then farmers may prefer a low-level research expenditure because high research expenditure would decrease commodity price significantly and thus harm the profits. For instance, Just, Alston, and Zilberman (2006) argue that US farmers do not encourage GMO (genetically modified organism) wheat is the concern about price effect in addition to resistance by EU to GMOs. In contrast, consumers will likely benefit from the research due to the decline in commodity price and therefore prefer a high-level R&D expenditure. Producers would benefit from innovation where the price elasticity of demand is high, and benefit from innovation that has high-income elasticity during periods when income is rising. Therefore, there will be more interest by producers in investment of R&D when products are exported, and private sectors will invest in products that improve food quality, which has high-income effect and generally higher price elasticity of demand. However, the demand for most agricultural products is very price inelastic; therefore, technical change tends to benefit consumers rather than producers, indicating that the social rate of return of agricultural research can be high, but the private rate of research may be low. This could in part explain the existence of agricultural commodity programs that compensate farmers for the loss of welfare because of public investment in agricultural research.

This idea appeared first in Cochrane (1979) and in Zilberman (1984), which showed that technological change tends to reduce the value of land; and government programs, by controlling supply, reduce the loss of farmers. Alston and Pardey (2021) argue that under the assumption of open economy and elastic demand for agricultural output, one can conclude that both consumer groups and farmer groups will benefit from R&D expenditure, and therefore farmer groups have little reason to oppose agricultural R&D.

Herring and Paarlberg (2016) point out that, first and foremost, compared with the era of green revolution when Malthusian anxiety dominated people's belief about the intertwined food-population relationship, famines in the 21st century became a much smaller concern. Therefore, political pressure to increase agricultural R&D for productivity is not as strong as that in the mid-20th century. Second, for consumers in developed countries, food is already abundant and inexpensive; thus, biotechnologies such as genetically modified crops do not bring them much benefit but impose health risk and uncertainties. This explains why genetically modified crops faced strong oppositions from consumer groups over the developed world.

Smith, Wesseler, and Zilberman (2021) review the literature on the political economy of both GMOs and gene-editing technologies. They argue that the opposition to these technologies comes from producers of products that will be replaced by the technologies (e.g., pesticides), whose prices will decline (e.g., wheat in Europe), and from organizations with ideological resistance to genetic manipulation (e.g., some environmental groups). These groups try to sway the consumer to be on their side. They do not necessarily strive to entirely ban the technology but erect regulatory barriers to delay its introduction and reduce the incentive to invest in its introduction.

Although many studies examine the political economy of agricultural policy in general (e.g., Rausser 1982; Swinnen 2010; Rausser et al. 2011; Anderson et al. 2013), only a few studies in the agricultural economics literature have focused on the political economy of agricultural experiment station research. Obviously, research on agricultural experiment stations can be influenced by various interest groups as well. One prominent example is the develop of mechanical tomato harvester in the 1950s and 1960s. As farm labor scarcity has been a persistent issue for US agriculture, researchers have long focused on how to develop automated technologies to economize labor use (San 2023). However, the automation innovations generally only benefits large farm, replacing farm workers and leaving small farms in great disadvantage in production costs. According to Carlisle-Cummins (2015), within five years of the introduction of the mechanical tomato harvester, 4,428 out of 5,000 tomato farms collapsed and about 32,000 farm workers were replaced by the machine. Thus, it was unsurprising that small tomato farmers and farm workers sued University of California for violating the 1887 Hatch Act that supports agricultural research to serve family farming. Although University of California ultimately prevailed in the lawsuit, its enthusiasm to continue labor-replacing research was largely dampened.

Rasmussen (1987) argue that public agricultural research, including experiment station research, should consider the demand from various interest groups like small farmers and consumers. Swallow and Mazzotta (2004) surveyed random voters and gauge their willingness to pay for research conducted by experiment stations. They find that the willingness to pay varies across different research types. Based on classic political-economic models, Zilberman (2006) and Rausser et al. (2011, Ch. 11) discuss various interest groups' (e.g., consumers, farmers, researchers, policymakers, and non-profit organizations) positions regarding investment in experiment station research. Moreover, a recent study by Smith et al. (2021) revisits the positions of these interest groups under current global challenges such as climate change and sustainable development of agriculture.

An interesting angle to view experiment station research is spatial spillover of innovations and the coordination among stations across the United States. Due to the scattered locations of experiment stations and the largely continuous distribution of farms across the United States, how do the experiment stations that focus on solving local agricultural issues serve entire US agricultural facing challenges of climate change and sustainable development? An early study by Evenson (1989) illustrates that geo-climate factors such as soil quality and water stress prevent technological spillover because, for instance, a new crop variety developed in one state may not perform well in another state due to their different environment. In the same vein, Moscona and Sastry (2022) document that the geographical R&D concentration in a few regions in the world reduces agricultural productivity in adopting regions by 58% because the "mismatch" between the crop growing environment in the innovating regions and the environment in the adopting regions. However, Kantor and Whalley (2019) find contradicting evidence. They show that productivity of land proximate to newly established agricultural experiment stations in the late 19th century increased during the first twenty years relative to land further away from these experiment stations. As the development of transportation and communication techniques in early 20th century, the productivity advantage of land proximate to experiment stations disappeared. Therefore, better understanding of the spatial spillover of experiment station research, perhaps through inter-state coordination of experiment stations, may have large potential to increase agricultural productivity and to address challenges facing agriculture. However, inter-state coordination can be challenging and may involve political economy issues.

PUBLIC AGRICULTURAL RESEARCH AND CLIMATE CHANGE

Agricultural innovations are expected to play a critical role in responding to the challenges imposed by climate change on agriculture. How has agricultural research responded to climate change? How efficient is the response, if any, in mitigating the negative impact of climate change on agriculture? An emerging literature attempts to answer these questions. In this section we provide a brief review of this literature.

By linking patent data and climate data, Miao and Popp (2014) and Miao (2020) have shown that agricultural innovations respond positively to climate change. For instance, Miao (2020) documents that innovations in drought-tolerant traits of crops are quite sensitive to drought severity measured by Palmer Drought Severity Index (PDSI). If the three-year average PDSI increase by one unit, one could expect that the number of patents about drought-tolerant traits would increase by 40%-60%. Similar findings are documented in Moscona and Sastry (2023) that links the numbers of new crop varieties with climate data in the United States.

How much have agricultural innovations alleviated the negative impact of climate change on agriculture? How much “more” innovations do we still need to overcome the negative impact? Two recent studies shed light on these questions. Built on the theory of directed innovation, Moscona and Sastry (2023) show that agricultural innovations have mitigated about 20% of climate damage since 1960 and are expected to mitigate 13% of projected climate damage by 2100, depicting a somewhat gloomy picture of agricultural innovation’s role in combating climate change. The findings in Lee et al. (2022) are consistent with those in Moscona and Sastry (2023). By using the yield contributions of genetically modified crops as a benchmark, Lee et al. (2022) calculate that yield damage of climate change by 2100 would be 2.8 to 6.3 times of the yield gains obtained from the current genetically modified crops.

This modest mitigating effect of agricultural research on climate change might help explain the mixed results exist in climate change literature regarding the extent to which US agriculture has adapted to the changing climate. Malikov et al. (2020) show that over 1950-2010, US corn and soybean yields had gradually become less sensitive to annual temperature or precipitation change, citing agricultural innovations as the underlying causes for the decreased responsiveness to temperature over time. To address the concerns that annual temperature variation may not reflect climate change, Yu et al. (2021) examine the responsiveness of crop yield to average temperature change between two periods far apart (e.g., 1958-1962 vs. 2013-2017) and find similar conclusions as those in Malikov et al. (2020). Furthermore, Yu et al. (2021) point out that while the decreased sensitivity of crop yields to extreme heat and extreme precipitation indicates the adaptation of agriculture to climate change, the decreased sensitivity of crop yields to *normal* temperature and precipitation indicates maladaptation. In other words, the adaptation to extreme heat and precipitation came with the cost of reduced ability to utilize normal temperature and precipitation, a finding that is consistent with that in Kahiluoto et al. (2019), who conclude that "current breeding programs and cultivar selection practices do not sufficiently prepare for climatic uncertainty and variability." Although Goodwin and Piggott (2020) find that genetically edited crops have lower yield risk under adverse climate when compared with traditional crops, Lobell et al. (2014, 2020) find that crop yield is becoming more sensitive to drought and overheat and attribute the increased sensitivity to the adoption of genetically modified crops. Roberts and Schlenker (2011, 2012) conclude that crop yields became less sensitive to precipitation but more sensitive to extreme heat over 1950-2005.

If we accept the results in Moscona and Sastry (2023) and Lee et al. (2022), then we may wonder why the contributions of agricultural innovations to mitigating climate change impact have been small. Zhang et al. (2023) find significant spatial heterogeneity in agricultural adaptation to climate change. However, they could not identify driving factors for this spatial heterogeneity. Their results indicate that agricultural adaptation is rather complex and that large-scale adaptation approaches, such as crop insurance and advanced seeds, may not suit all locations because local management technologies and endowments differ. This would suggest that the R&D efforts and agricultural policy designs that aim to enhance agricultural adaptation to climate change should be tailored to local contexts. However, doing so might inhibit technological spillovers and cause productivity disparities across regions as documented by Evenson (1989) and Moscona and Sastry (2022). Therefore, balancing climate change adaptation and cross-region productivity equity may come to be a policy dilemma, which is a political economic issue to be examined in future research.

A BIBLIOMETRIC ANALYSIS

We conducted a comprehensive bibliometric analysis focusing on the political economy of public agricultural research in the context of climate change by using research articles obtained from the Web of Science (WOS). We include articles about the role of land grant universities or experiment stations, agricultural research and development (R&D), political economy, and climate change, all within the overarching domain of economics as well as agricultural economics and policy. We conducted an extensive search using relevant keywords such as agricultural innovation, agricultural research, political economy, R&D expenditures, experiment station, land grant universities, and climate change-innovation. Our search encompassed titles, author keywords, keywords plus, and abstracts of publications indexed in the WOS across various search settings. Subsequently, we thoroughly reviewed the abstracts and excluded those that deviated significantly from our focus. As a result, we identified and selected 174 papers that closely align with the discussions presented above.

We used software Biblioshiny and Vosviewer to analyze our bibliometric data based on the full record and cited references of the selected publications, which the analysis explores the interconnections and networks between publications by utilizing established links such as citation, co-citation, keyword co-occurrence, and bibliographic coupling. The co-citation relationship between two publications indicates that both are cited by at least one article, whereas bibliographic coupling suggests that they share at least one article in their reference list. The strength of the co-citation relationship between two publications grows as the number of publications that co-cite both of them increases. As the number of shared references between two publications grows, the bibliographic coupling relationship between them gains in strength. The co-occurrence of keywords refers to two or more keywords appearing together in one document. These links are the foundation for clustering publications within a sample (Van Eck & Waltman, 2007 and 2017). The bibliometric analysis utilizes distance-based maps to identify similarities based on the links explained above among articles, using a mapping strategy proposed by Van Eck & Waltman (2007).

Specifically, the distances on the map indicate the relatedness between the items based on the direct citation relationship between them; the closer two items on the map, the higher their relatedness. The Vosviewer clusters items that are relatively strongly related to each other by maximizing a quality function that considers direct citation relationships between the articles (Van Eck and Waltman, 2017; Waltman et al. 2010). Clusters are represented by different colored bubbles on the map and the size of the bubbles reflects the importance of items based on the number of citations (Van Eck & Waltman 2014), and the curved lines between bubbles indicate citation relations between publications (Van Eck & Waltman 2017). In the keyword analysis, the frequency of keyword occurrence determines the size of bubbles (i.e. the larger bubble, the higher occurrence of that keyword), and relatedness is calculated by using a formula calculating the co-occurrence frequency of items as is shown by Van Eck and Waltman (2007); i.e. the larger the bubble the higher the occurrence of that keyword, and the closer the distance for two items (e.g., keywords) the higher the co-occurrence of those items. Furthermore, the presence of curved lines on the map can also indicate the co-occurrence of these items (Van Eck and Waltman, 2017), even if these items are situated in separate clusters that are distantly positioned.

On the other hand, changes in research trends and priorities can lead to the prominence of different keywords or themes over time, i.e. a trending topic might cause a sudden increase in connections between specific keywords, or some keywords get more focused by researchers in a period. The thematic stand and evolution of the literature can be tracked by using Biblioshiny in R that use keyword and content analyses (Callon et al. 1991, Coulter et al. 1998) based on the co-occurrence of keywords and the changing relationships between keywords over time (Aria et al. 2020).

Figure 1 illustrates the keywords' co-occurrence clusters, which are mostly repeated ones from 462 different keywords used by authors, which are the main concepts of our research. Keyword co-occurrence refers to the occurrence of two or more keywords within the same document or publication. It measures the frequency and patterns of keywords appearing together, indicating the relationships and associations between different concepts within a body of literature. The greater the number of shared keywords between two documents, the more similar the publications are, indicating a higher likelihood of belonging to the same research field (Cobo et al. 2011b). By analyzing the size or prominence of keywords on the map, researchers can identify the most important or central terms within the dataset (Zhu et al. 2015). It is also helpful to highlight the interdisciplinary connections or overlaps between different research areas since co-occurrence relationship enables us to see connected the areas of cross-disciplinary collaboration or knowledge transfer (Radhakrishnan et al. 2017). Larger or more prominent keywords indicate higher frequency and greater relevance within the publications.

Within our research focus, the keywords "agricultural research," "land grant universities," and "experiment stations" are encompassed within the green cluster located on the left side of the Figure. This cluster exhibits relatively small bubbles and weak connections, suggesting the need for further research to promote knowledge dissemination and enhance our understanding of the role played by experiment stations and land grant universities in the political economy of agricultural innovation. Smaller bubbles and weak connections (by curved lines) are indicative of less frequent usage and lower co-occurrence frequencies. Likewise, the concept of climate-smart agriculture, represented by the yellow cluster on the right side of the figure, and the concept of agricultural biotechnology, represented by the neon blue cluster on the upper right side, appear distanced from the center with limited connections and relatively small impacts.

The clusters relatively near the center of the figure show more relevance to the common idea of the dataset. Within this line, the keywords "climate change," "innovation," "research and development," "adaptation," "induced innovation," "spillovers," "agricultural R&D," "productivity," and "rate of return" emerge at the lower middle of the figure, exhibiting stronger impacts and extensive networks. These keywords can be considered the most prominently focused topics in the realm of political economy of agricultural innovation research. Also, upper middle of the figure depicts relatively more networks and proximity with the clusters located on the upper left side, focusing on the terms such as biotechnology, bioeconomy, GM crops, genetic engineering, political economy, biotechnology, and genetically modified organisms.

Through the examination of keyword occurrences over time, emerging trends and shifts in research focus can be identified. Variations in the prominence or presence of specific keywords can indicate the evolving interests and priorities within the field, termed thematic evolution. Thematic evolution maps enable researchers to visualize and interpret the changing landscape of research topics or themes over time, offering valuable insights into the dynamics, trends, and emerging areas within a specific field of study (Cobo et al. 2011b). Figure 2 depicts the thematic evolution of the most focused concepts throughout the predetermined periods fitting well into the publication years and keyword frequency. It provides a visual depiction of the evolving nature of subthemes within a field. It illustrates the patterns of emergence, disappearance, merging, and reappearance of themes over time (Rosvall and Bergstrom 2010). The size of nodes in Figure 2 reflects the keyword occurrence frequency (i.e., how many times the keyword is used by publications in that period).

The first period of the evolution heavily relied on political economy and technical change, and then they evolved into political economy, innovation and agriculture keywords in the second period. In the second period, the term political economy is still commonly used and co-occurs with the term agriculture. That is why the belt comes from the first period to the second by splitting into political economy and agriculture keywords. The third period is enriched by biotechnology and agricultural R&D in addition to the items of the second period. In this period, the term political economy is still prominent after the term biotechnology, but they disappear in the recent period by converging into digital agriculture, climate change and bioeconomy. This means that those keywords are used more in the recent period by having relatively higher co-occurrence with emerging items, and gray belts show the direction of evolution based on the co-occurrence frequency of keywords (Aria et al. 2020, Cobo et al. 2011b). The current period in which innovation and agriculture keywords still take place shows that the political economy discussions on agricultural innovation have increasingly focused on digital agriculture, climate change and bioeconomy, suggesting a shifting trend and growing emphasis on these topics within the field.

Figure 3 displays a thematic map which is a visual representation of the main themes discussed in the selected set of publications. The map positions key subject themes based on their density and centrality. Density refers to the degree of development of a theme, centrality denotes its relevance within the whole research landscape. Approximately, the more publications exist under a theme, the higher the development level of the theme; the more publications cite the articles within a theme, the higher the centrality of this theme. Bubbles on the map are labelled using the keywords that have the highest occurrence value (Khare and Jain 2022). To gain a better understanding of the keywords, we included some top keywords within each bubble. The size of a bubble is proportional to the number of occurrences of the corresponding word. The thematic map is divided into four regions based on the density and relevance degree, representing niche, motor, emerging/declining, and basic themes. Accordingly, political economy, adaptation, research and development, and productivity growth are clustered among motor themes with the largest bubbles, considered well-developed and integral aspects within the field, serving as essential components for organizing the study topic. Basic themes hold significant relevance in a field, yet they exhibit relatively limited development with the keywords productivity, adoption, economics, science, industry, government, variability and adaptive capacity. Emergings or declinings show low levels of both density and relevance, which are characterized by being in a state of emergence or decline, such as global political economy, governance, transition, faculty, university, determinants and dynamics. Finally, niche themes, including the keywords agriculture, insights, knowledge, Canada, diffusion and globalization, demonstrate a high density of content but possess low centrality within the field, which is attributed to relative importance. While they hold marginal significance within the area with established internal connections, their external connections are negligible.

Another important output of our analysis is bibliographic coupling as a measure of similarity, which is a useful visualization technique for quantifying the overlap of shared references between two documents. When at least one cited reference is present in the reference lists of both documents, the documents are considered to be bibliographically coupled. The bibliographic coupling strength between two documents is determined by the extent of shared references. In other words, the greater the overlap in references, the stronger the bibliographic coupling. This premise is based on the idea that when two documents, authors, or sources share many similar references, they are likely discussing the same topic or subtheme (Kessler 1963, Van Eck and Waltman 2014, Aria and Cuccurullo 2017).

Figure 4 reveals a higher density of connections for bibliographic coupling on the right side, covering the green, yellow, brown and neon blue clusters. The distances on the map indicate the strength of relationships between the articles, while the connections between them are represented by curved lines showing the citation relationship between the items analysed. The size of the bubbles on the map reflects the importance of the articles based on the total citations, and the color represents the affiliation of a specific cluster. Pardey et al. (2010) have the highest connections, while Alston et al. (2009) have the highest citation count in the whole collection by leading the brown cluster with the general theme of agricultural research, productivity, agricultural R&D, spillovers, intellectual property, market failures. Similarly, green, neon blue and yellow clusters are mainly dominated by the papers of Phillip Pardey and Julian Alston. The neon blue cluster primarily consists of public and private agricultural research and extension, grant funds and productivity with the leading papers of Alston et al. (2011), Jin and Huffman (2016), Huffman et al. (2006), Wang et al. (2013), Vilavicencio et al. (2013). The green cluster heavily focuses on the keywords rate of returns and r&d returns with the leading papers of Hurley et al. (2014 and 2017), Pardey et al. (2016), and Rao et al. (2020). The yellow cluster highlights the global concerns, climate change and agricultural innovation nexus, dominated by the seminal works of Lybbert and Sumner (2012), Alston and Pardey (2014), Miao and Popp (2014), Miao (2020), Nyantakyi-Frimpong (2020), Auci et al. (2021) and Moscano and Sastry (2023). It is important to note that the items within each cluster may not always align perfectly by using the same title, keywords or abstract. Rather, they lean towards a general theme with some notable papers within the collection and demonstrate a strong bibliographic matching score with them.

Moving slightly away from the high-density region surrounded by brown, yellow, neon blue and green clusters, the purple collection primarily centres around growth, induced innovation and technical change through the seminal works of Smithers and Blay-Palmer (2001), Olmstead and Rhode (1993), Cowan et al. (2015), Thirtle et al. (1998), Clark et al. (2012). Notably, the focus point of Byerlee et al. (2009) is moving away from this theme by highlighting the diverse contributions of agriculture to economic growth, poverty reduction, gender equity, food security, and environmental sustainability. Similarly, Fuglie and Toole (2012) demonstrate proximity to the themes of the brown and neon blue groups through their emphasis on public and private agricultural research.

The blue cluster dominated by influential works such as Falkner (2007), Newel (2009), Herring and Paarlberg (2016), Klepek (2012), Wield et al. (2010), Smith et al. (2021), Walls et al. (2005), and Zilberman et al. (2015), heavily relies on the exploration of agricultural biotechnology, gene editing, and genetically modified (GM) crops in line with the political economy. This cluster exhibits a higher level of coherence and relevance with the other publications within the collection, underscoring its substantial thematic focus and the significant contributions made by these authors in advancing the discourse surrounding these cutting-edge topics in agricultural research. While primarily clustered within the red collection, Clapp (2021) is positioned near the center of the blue cluster due to its thematic focus on the political economy of herbicide-dependent agriculture since it effectively connects the issue to the rise of agricultural biotechnology and references. Similarly, Borras (2016), located in the red cluster, delves into the rise of flex crops and commodities, attributing their development to agricultural biotechnology. However, other members of the red cluster can not construct a strong relationship and coherence within the group. Only a few items of the red collection create a distinct theme and exhibit coherence by cumulating on digital agriculture through the documents of Rotz et al. (2011), Hackfort (2021), Abdulai (2022) and Oui (2019). Another cluster that can be merged with the theme of digital agriculture in the red collection is emerging in pink colour, particularly centered around climate-smart agricultural innovation because digital agriculture can play a significant role in supporting climate-smart agricultural innovation by providing tools and technologies that enable farmers to make informed decisions based on real-time data, improve resource efficiency, and adapt to changing climatic conditions. This emerging cluster is prominently represented by the works of Geda and Kuehl (2021) and Teklu et al. (2022, 2023a, 2023b).

CONCLUDING REMARKS

In this paper we first reviewed some major theories in technical innovation and political economy. We then discussed public agricultural research expenditure in the United States and tried to explain why it has been decreasing in the past two decades from a political economy point of view. Economic literature on experiment stations was also reviewed, with a focus on spatial spillover of experiment station research. By focusing on climate change, we highlighted the dilemma between climate change adaptation and cross-region productivity equity, which calls for future research from the perspective of political economy as the global challenges facing agriculture switching from productivity to sustainability.

The bibliometric analysis shows the need for future research on the role of land grant universities and experiment stations, digital agriculture, and climate-smart agriculture as they are emerging topics in the nexus of agricultural research, political economy, and climate change. Also, thematic evolution flow discloses the keyword “bioeconomy” in recent times, which is driven by agricultural innovation by improving resource efficiency and fostering the sustainable use of biological resources (Karp et al. 2015). Climate change is a prominent subject of recent literature, aligning with the political economy perspective. This is further substantiated by our thematic map that highlights the emerging theme of the global political economy, particularly relevant to addressing global common problems and global public goods. Future research can contribute to the understanding of the political economy of agricultural innovation by exploring (i) the role of climate-smart agriculture in addressing climate change challenges and its political economy implications, (ii) the potential of digital agriculture in driving agricultural innovation and its political economy implications, (iii) the evolving relationship between the bioeconomy and agricultural innovation from various aspects such as including the utilization of bio-based feedstocks, bioenergy production, and value-added products, and (iv) the global political economy aspects of agricultural innovation for the role of international institutions, trade agreements, and policy coordination.

The present paper only focuses on public agricultural research, although private agricultural research has become increasingly important in the United States (Fuglie et al., 2012; Fuglie and Toole, 2014). Public and private research is complementary quite frequently. As Zilberman et al. (2022) suggest, many innovations (e.g., agricultural biotechnology) originated from the public sector that transferred the rights to the private sector to develop the technology. Taylor and Zilberman (2017) give another example: Private companies sell drip irrigation equipment, and public research and extension developed new varieties and new application technologies to use with drip irrigation in different crops. Moreover, the public sector developed formulas for many pest control strategies that were implemented by the private sector. This is the case for both chemical treatments and Integrated Pest Management, where extensions frequently train private pest control advisors. To fully understand the synergy between public and private research in the aspect of addressing global challenges could be a fruitful direction for future research.

Zilberman et al. (2022) introduce the concept of "innovation supply chain," making the point that our understanding of innovation should be placed in a broader, symbiotic context that covers both innovation supply chain and product supply chain. Along the same lines, in a recent National Bureau of Economic Research working paper Guzman et al. (2023) propose that innovation should be understood from the perspective of regional innovation ecosystem, defined as “interconnected set of institutions—universities, corporations, government, start-ups, and investors—within a geographic region whose connectivity allows each organization and researcher in that region to leverage the knowledge, resources, and specialized capabilities of other institutions and individuals within that location.” Examining the role of public agricultural research institutions (e.g., land-grant universities and agricultural experiment stations) from the perspective of innovation supply chain or regional innovation ecosystem may be another interesting direction for future research.

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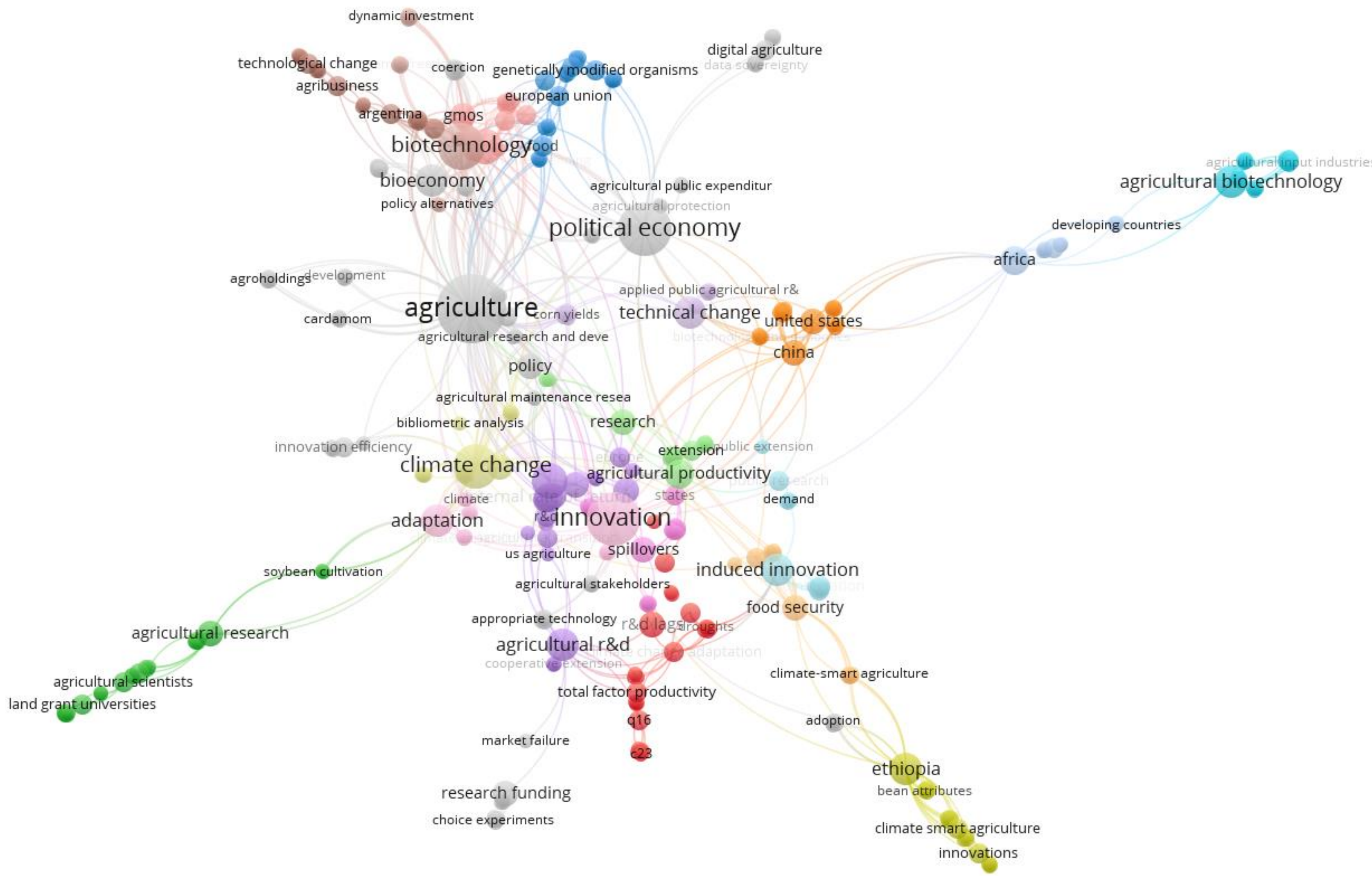

Figure 1: Clustering of keyword occurrence

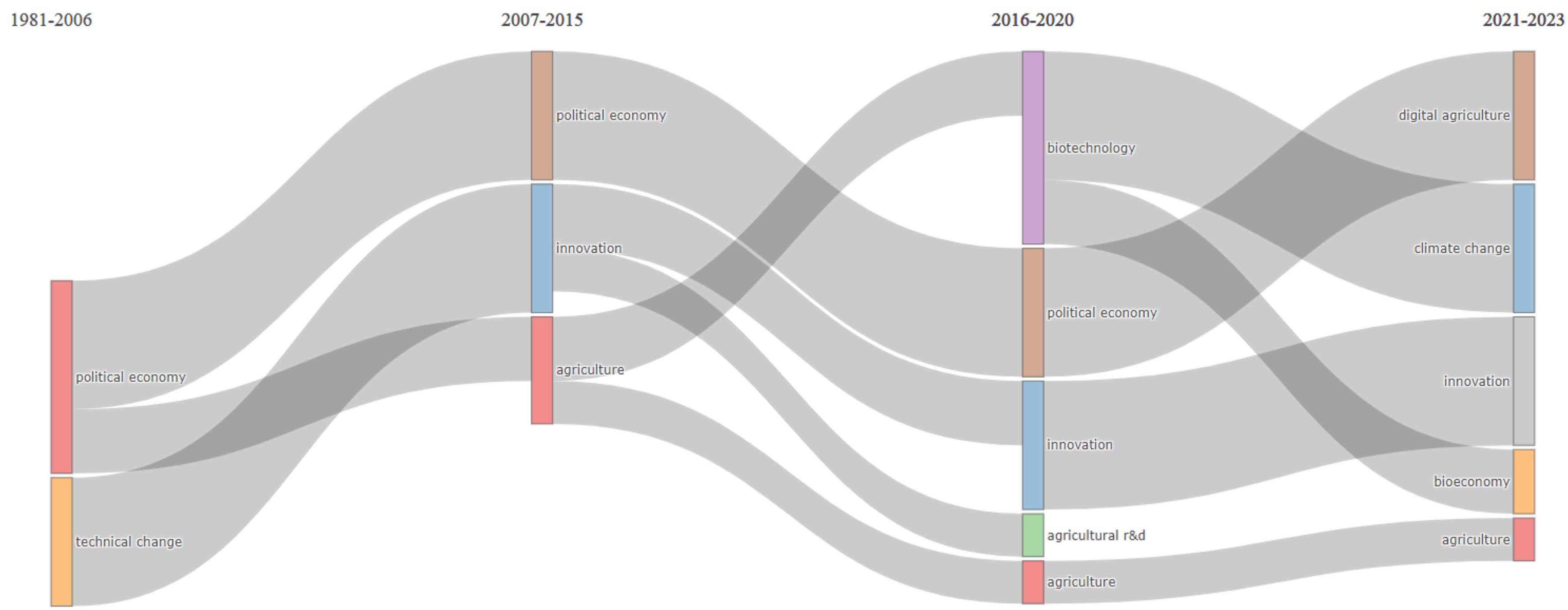

Figure 2: Thematic evolution

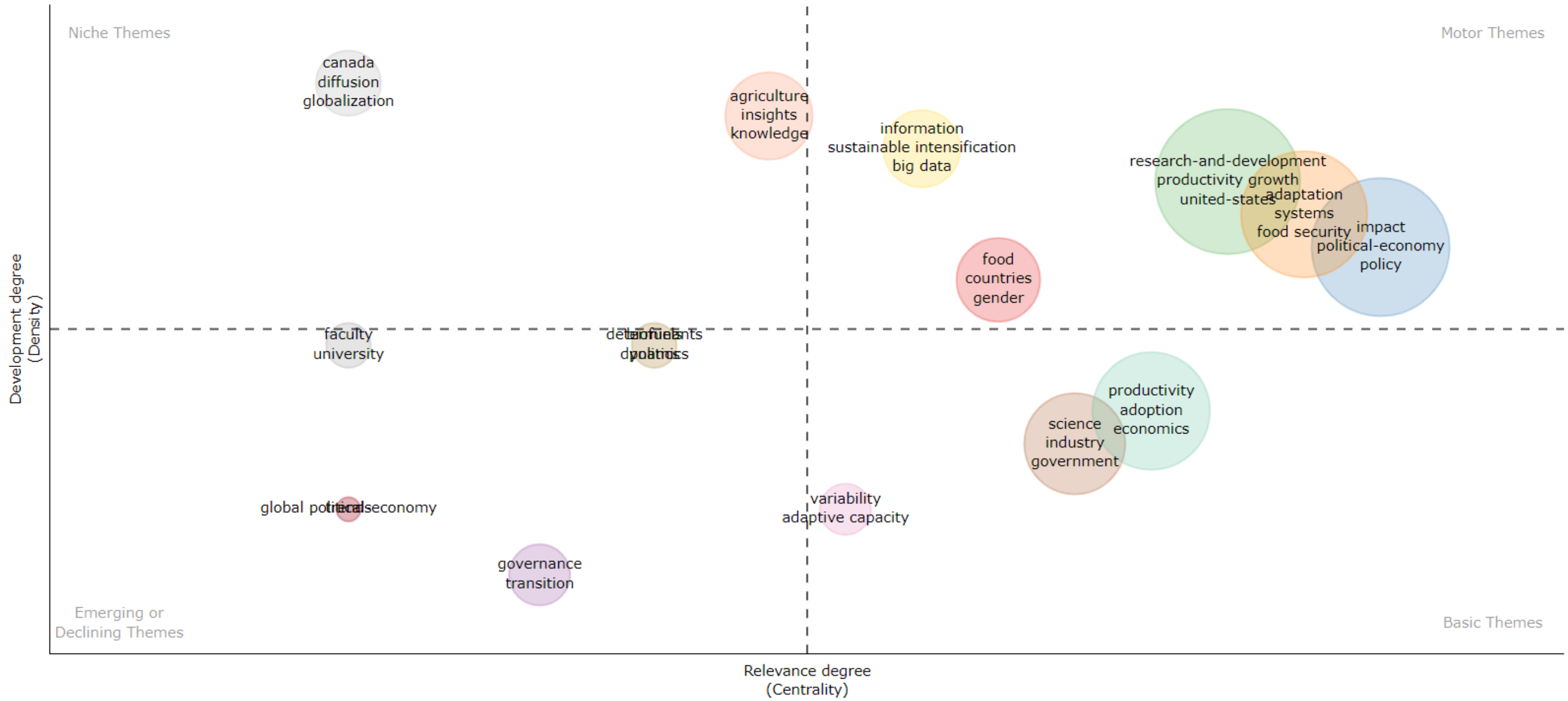

Figure 3: Thematic map

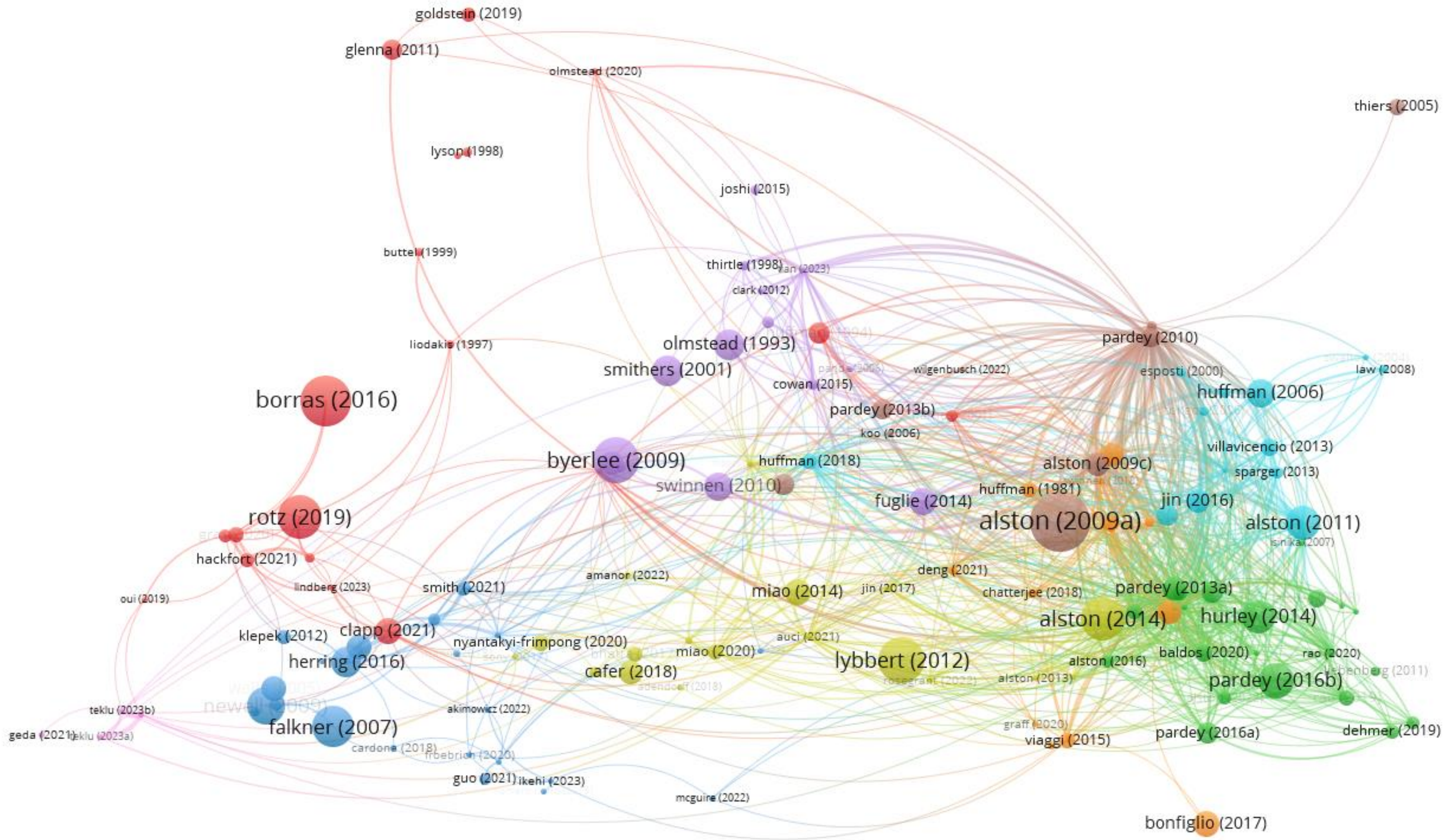

Figure 4: Clustering of bibliographic coupling with connections