Unveiling Research Patterns in Precision Agriculture: A Comprehensive Network Analysis of ICPA Proceedings

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Abstract.

The International Conference on Precision Agriculture (ICPA) is one of the most influential global forums dedicated to advancing technologies, methodologies, and scientific understanding in the domain of precision agriculture. Since its inception, the conference has served as a central platform for disseminating innovations in data-driven crop management, sensor technologies, spatial analysis, automation, and decision-support systems. Now in its 17th edition, the ICPA has accumulated more than three decades of contributions, forming a substantial body of scientific knowledge and a robust international research community. Despite its relevance, a comprehensive historical and bibliometric assessment of the event's scientific output and collaborative structures has not yet been systematically developed. The objective of this study is to analyze the history of the ICPA by examining all publicly available proceedings (2008-2024). Specifically, the study aims to (i) identify the most prolific actors (authors, institutions, and countries) who have contributed significantly to the advancement of precision agriculture through this venue, and (ii) map the major co-authorship networks that have emerged and consolidated across the event's history. These objectives address the gap in understanding how the community has developed over time, who its central contributors are, and how collaborative patterns have shaped the dissemination of knowledge within the field. The methodology integrates data extraction from all ICPA proceedings available online. Co-authorship networks were modeled using graph-based analytical techniques, enabling detection of highly connected subgroups, influential nodes, and trends in collaboration. Quantitative outputs include a ranked list of the top contributing actors based on publication frequency, network centrality, and sustained participation across conference editions. Additionally, the study identifies the principal co-authorship clusters that have formed the structural backbone of the ICPA research community. These clusters reveal long-term scientific partnerships, cross-institutional collaborations, and the geographical distribution of influential research groups. The findings offer a systematic and quantitative

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characterization of the individuals and collaborative networks that have shaped the recent history of the ICPA. Beyond descriptive metrics, the results provide a formal recognition of the researchers whose contributions have been foundational for the evolution of precision agriculture as a scientific discipline. By mapping these networks and identifying leading contributors, the study enhances understanding of how knowledge production and cooperation occur within this international community, offering insights that may guide future collaborations, strategic planning, and the continued strengthening of the conference as a reference venue in the field.

Keywords.
Bibliometrics, Co-Authorship Networks, Precision Agriculture, Scientific Collaboration, Social Network Analysis

Introduction

Precision agriculture (PA) has evolved as a transformative paradigm driven by advances in digital and data-intensive technologies, with research expanding rapidly in recent years (Basso and Antle, 2020; Adewuyi et al., 2024; Getahun et al., 2024; Rejeb et al., 2024; Kabir et al., 2025; Bhat et al., 2026). Within this context, the International Conference on Precision Agriculture (ICPA) has played a central role in shaping the field by providing a dedicated forum for the dissemination of research on data-driven crop management, sensing technologies, spatial analysis, and decision-support systems. Since its first edition in 1992, the sustained activity of the conference has contributed to the consolidation of a substantial body of scientific output and to the formation of a globally interconnected research community characterized by strong collaboration networks.

Despite the importance of the ICPA as a reference venue, there is still a lack of systematic studies examining its scientific production and the structure of its research community. In particular, little is known about how collaboration patterns have evolved over time, which authors have played central roles in knowledge production, and how institutional and geographical contributions have shaped the conference's trajectory. Understanding these aspects is essential for characterizing the dynamics of knowledge exchange and for supporting future collaboration strategies within the PA community.

Bibliometric analysis and social network analysis provide a robust framework for investigating such questions. By modeling co-authorship relationships as networks, it is possible to identify influential contributors, detect collaboration clusters, and analyze the structural properties that underpin scientific communities (Silva and Silva-Mann, 2021; Liu et al, 2024; Camargo, 2025). These approaches have been widely applied in other scientific domains but remain underexplored in the context of ICPA.

In this study, we present a comprehensive bibliometric and network-based analysis of all publicly available ICPA proceedings (2008–2024). The analysis is conducted across multiple levels (authors, institutions, and countries), allowing for an integrated view of the community structure and its evolution over time. Co-authorship networks are constructed to identify highly connected subgroups, central actors, and long-term collaboration patterns.

The main contributions of this work are threefold: (i) to identify the most prolific and influential actors contributing to the advancement of precision agriculture through ICPA; (ii) to map the major co-authorship networks that have emerged and consolidated throughout the conference's history; and (iii) to identify the principal research topics addressed within ICPA. By providing a quantitative and structural characterization of the ICPA community, this study advances the understanding of how scientific collaboration and knowledge production have evolved within this important research venue.

Materials and Methods

Study Design

This study is characterized as applied research with a descriptive objective and a quantitative approach. A document-based methodology was adopted, involving the systematic collection and analysis of publicly available publications from the International Conference on Precision Agriculture (ICPA) proceedings. The methodological workflow comprised four main stages: (i) metadata collection, (ii) metadata preprocessing, (iii) generation of the co-authorship network, and (iv) computation of actor-level network metrics.

Metadata Collection and Preprocessing

Metadata were collected using a web scraping approach, enabling automated extraction of structured information from web pages. A custom scraper was developed to retrieve all available records from the conference's website (https://www.ispag.org/icpa/proceedings/?&action=conference). The scraping process was executed on November 21, 2025, at 17h, capturing a complete snapshot of publicly accessible data at that time. The dataset includes publications from 9th (2008) through 16th edition (2024), covering eight earliest editions of the event history.

A preprocessing phase was required to ensure data consistency. Although author names followed a well-defined pattern, institution names appeared in multiple variants (e.g., "University of Nebraska"; "University of Nebraska, Lincoln"; "University of Nebraska-Lincoln"; and "University of Nebraska - Lincoln"). Similar inconsistencies were observed in country names (e.g., Brazil vs. Brasil), as well as in records where institution names were listed without an associated country.

To address these issues, the preprocessing stage employed natural language processing (NLP) techniques. Specifically, a 3-gram–based approach was used to identify and standardize institution and organization names, enabling more reliable aggregation and analysis.

In total, metadata were compiled, resulting in 1,731 contributions (including oral and poster presentations), involving 4,046 authors, from 63 countries, using 3,874 keywords.

Co-authorship Network Construction

A co-authorship network was constructed based on graph theory principles, forming the basis for Social Network Analysis (SNA). In this network:

- Nodes represent individual actors at multiple aggregation levels (authors, institutions, and countries), or keywords;
- Edges represent co-authorship relationships between actors or keywords within the same publication;
- The network is undirected, as actor or keyword order was not considered;
- Edge weights correspond to the frequency of co-authorship between pairs of actors.

The resulting graph captures the structure of scientific collaboration across the entire temporal span of the dataset.

Network Metrics and Author Relevance

Network analysis was performed using Gephi software (Bastian et al, 2009). The following metrics were computed to assess actor relevance and structural roles within the network:

- Number of Publications (Pub): Total number of publications associated with each actor, regardless of authorship position.

- Degree (Deg): Number of unique collaborators linked to a given actor, reflecting collaboration breadth and connectivity within the network (Kabir et al., 2025).
- Betweenness Centrality (BC): Measures the extent to which an actor acts as an intermediary in the network, connecting different subgroups. Authors with high BC are considered critical for information flow and network cohesion (Jiang et al., 2023).
- PageRank (PR): Adapted from the original algorithm for ranking web pages, this metric captures recursive influence, highlighting actors connected to other influential actors identifies (Rejeb et al., 2024).
- Community Detection (Com): Collaboration communities were identified using the Louvain method. Communities were ranked by size, with Community 1 representing the largest group, followed by Community 2, and so forth.

  Figure 1 summarizes a methodology overview of this study.

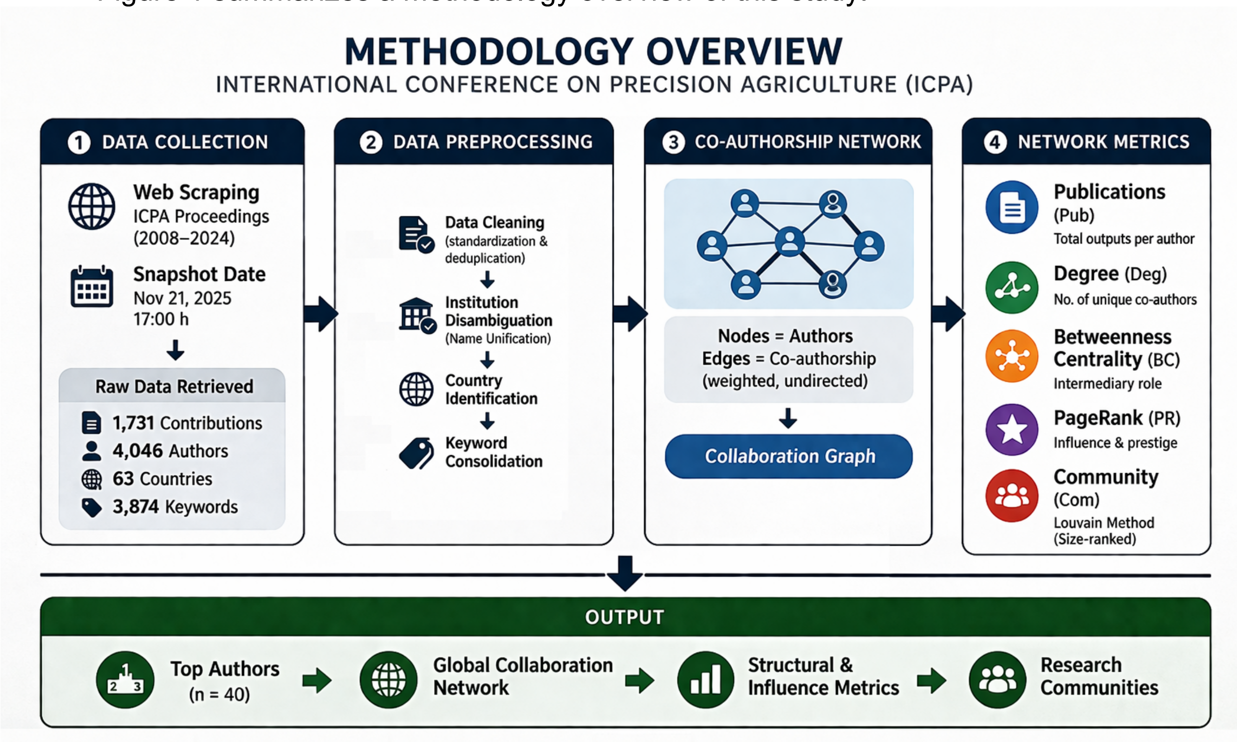

Fig 1. Methodology overview

Results and Discussion

The bibliometric and network-based analysis of the ICPA proceedings reveals a structured and moderately centralized scientific community, characterized by the coexistence of highly influential actors and a broader base of peripheral contributors. Across all levels of analysis (authors, institutions, and countries) the results indicate that knowledge production within the ICPA is driven by a relatively stable core of contributors, while maintaining a degree of openness to new participants.

Author-Level Analysis

The co-authorship network at the author level exhibits a heterogeneous structure, in which a small subset of researchers concentrates a significant portion of collaborations. High values of degree centrality indicate that these authors are highly active in collaborative research, while elevated betweenness centrality suggests their role as intermediaries connecting otherwise disconnected subgroups. This dual characteristic highlights the presence of key individuals who not only produce extensively but also facilitate knowledge integration across the network (Table 1).

However, the distribution of centrality measures suggests a moderate level of fragmentation. Although core actors are well connected, many authors remain located in sparsely connected regions of the network. This pattern is consistent with emerging or interdisciplinary fields, where collaboration is still consolidating and not yet fully cohesive. In this sense, the ICPA community appears to balance consolidation and expansion, reflecting both maturity and ongoing diversification.

The use of PageRank further refines this interpretation by identifying actors whose influence extends beyond direct collaboration counts. Authors with high PageRank are not necessarily the most prolific, but are connected to other influential contributors, indicating a recursive structure of scientific influence. This distinction reinforces the importance of considering multiple centrality measures, as productivity alone does not fully capture scientific impact within collaborative environments.

Table 1. Top-40 authors ranking.

Rank	Author	Pub	Deg	BC	PR	Com
1	J. P. Molin	**35**	56	0,027517	0,002558	17
2	Y. Miao	34	**91**	**0,069492**	0,002956	3
3	V. I. Adamchuk	31	76	0,024243	0,002765	12
4	J. P. Fulton	31	73	0,040907	**0,003013**	2
5	R. Khosla	30	65	0,052501	0,002182	10
6	N. R. Kitchen	29	69	0,016430	0,002480	8
7	A. Sharda	29	49	0,021060	0,002240	6
8	C. L. Bazzi	26	48	0,024847	0,001698	7
9	S. Shibusawa	26	30	0,004785	0,001415	1
10	L. Longchamps	22	41	0,009009	0,001480	10
11	T. Griffin	21	39	0,027641	0,001548	6
12	I. Ciampitti	20	55	0,021881	0,002108	6
13	P. S. Magalhaes	20	53	0,009161	0,001678	7
14	K. Schenatto	20	36	0,005202	0,001341	7
15	B. V. Ortiz	19	63	0,030743	0,001904	9
16	D. W. Franzen	19	55	0,013265	0,002082	8
17	J. D. Luck	19	43	0,016052	0,001701	2
18	K. A. Sudduth	18	26	0,004532	0,001005	8
19	Y. Zhang	17	64	0,035878	0,001644	1
20	E. G. Souza	17	33	0,006577	0,001164	7
21	M. Kodaira	17	20	0,001940	0,000992	1
22	S. Chung	16	47	0,013891	0,001630	20
23	A. Cambouris	16	36	0,006874	0,001375	12
24	R. B. Ferguson	15	54	0,020899	0,001545	8

25	C. Yang	15	37	0,015747	0,001153	4
26	S. A. Shearer	15	31	0,002081	0,001466	2
27	Q. Zaman	15	27	0,007150	0,001072	26
28	D. Mulla	14	53	0,031062	0,001460	3
29	G. Vellidis	14	49	0,020460	0,001491	9
30	R. Y. Inamasu	14	49	0,006808	0,001624	22
31	L. Thompson	14	33	0,013074	0,001226	13
32	L. Puntel	14	32	0,009273	0,001229	13
33	A. A. Farooque	14	26	0,000655	0,001070	26
34	R. A. Ortega	14	24	0,003816	0,000989	13
35	P. M. Kyveryga	14	23	0,003409	0,001025	6
36	L. Lacerda	13	56	0,030140	0,001455	3
37	S. Phillips	13	43	0,012334	0,001501	21
38	L. R. Amaral	13	35	0,009292	0,001060	7
39	I. J. Yule	13	25	0,000060	0,001186	28
40	T. J. Esau	13	21	0,000629	0,000892	26

Figure 2 presents the top-ranked authors and their respective collaboration patterns within the ICPA co-authorship network. Colors other than gray represent the eight largest co-authorship communities identified through the Louvain method. The seventh-largest community, highlighted in green, includes four authors within the ranking, indicating a relatively cohesive subgroup with notable representation among the most productive researchers. Similarly, community 8 (light brown) also comprises four top-ranked authors, reinforcing the presence of well-defined and productive collaboration clusters within the network.

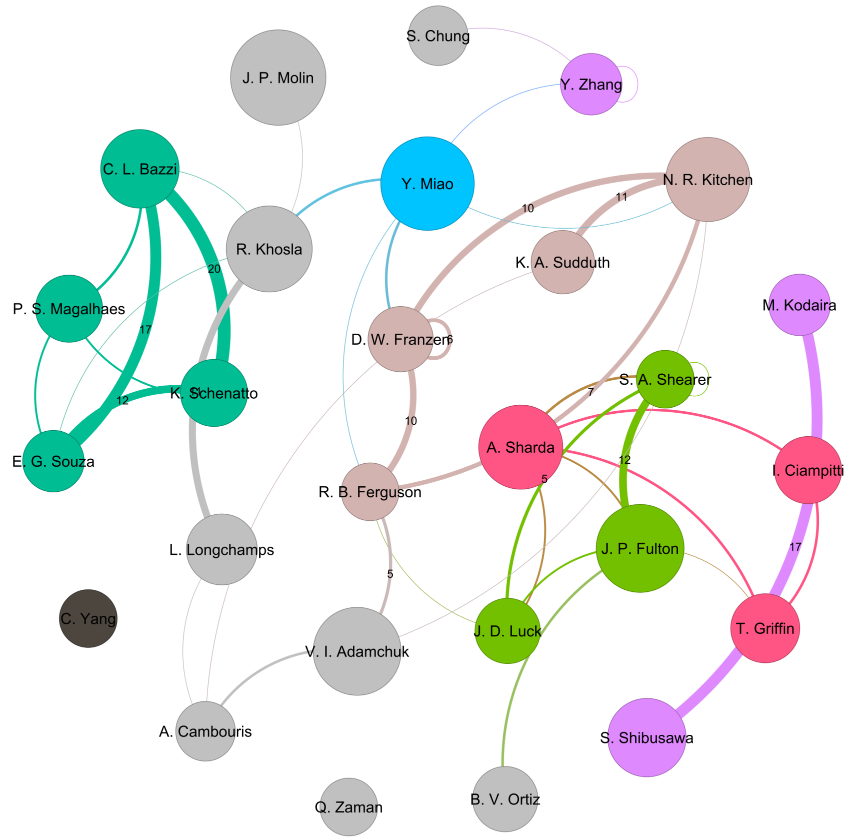

Fig 2. Top-ranked authors and their respective collaboration networks within the ICPA co-authorship structure.

Institutional and Country-Level Dynamics

At the institutional level, the network reveals a concentration of influence in a limited number of organizations, many of which maintain long-term participation in the conference (Table 2). These institutions act as hubs of knowledge production and collaboration, often bridging different research groups and geographical regions. The presence of such hubs suggests a level of institutional stability that contributes to the continuity and identity of the ICPA community.

Nevertheless, the network also exhibits signs of regional clustering, with institutions more likely to collaborate within geographically or culturally proximate groups (Figure 3). While this pattern can facilitate efficient collaboration, it may also limit the diversity of knowledge exchange if cross-regional connections are not sufficiently developed. The identification of institutions with high betweenness centrality is particularly relevant in this context, as these actors play a critical role in connecting otherwise separated clusters and promoting international integration.

Table 2. Top-20 institutions ranking.

Pos	Acronym	Institution	Pub	Deg	BC	PR	Com
1	USDA-US	United States Department of Agriculture	**136**	**24**	**0,168946**	**0,087515**	1
2	KState-US	Kansas State University	73	13	0,047387	0,025150	1
3	UNL-US	University of Nebraska-Lincoln	53	15	0,054461	0,035889	1
4	DSU-US	Dakota State University	53	14	0,021916	0,070263	4
5	UGA-US	University of Georgia	41	7	0,038095	0,026599	2
6	UFL-US	University of Florida	38	13	0,074902	0,027307	2
7	UMN-US	University of Minnesota	36	16	0,123094	0,044362	1

8	USP-BR	Universidade de São Paulo	36	4	0,141080	0,016297	3
9	Missouri-US	University of Missouri	31	13	0,075936	0,036231	1
10	OKState-US	Oklahoma State University	31	10	0,101012	0,019644	1
11	NDSU-US	North Dakota State University	31	9	0,002427	0,042839	4
12	MCGill-CA	McGill University	30	3	0,003725	0,016798	7
13	OSU-US	Ohio State University	29	8	0,015351	0,012917	1
14	ColoState-US	Colorado State University	28	8	0,069624	0,022634	1
15	CAU-CH	China Agricultural University	25	9	0,045882	0,026054	1
16	Unicamp-BR	Universidade de Campinas	24	2	0,100408	0,009187	3
17	UTokio-JP	University of Tokyo	24	0	0,000000	0,003268	
18	UC-US	University of California	22	10	0,028110	0,016033	1
19	SDSU-US	South Dakota State University	22	7	0,003719	0,029448	4
20	UOGhelph-CA	University of Guelph	21	3	0,001156	0,017141	7

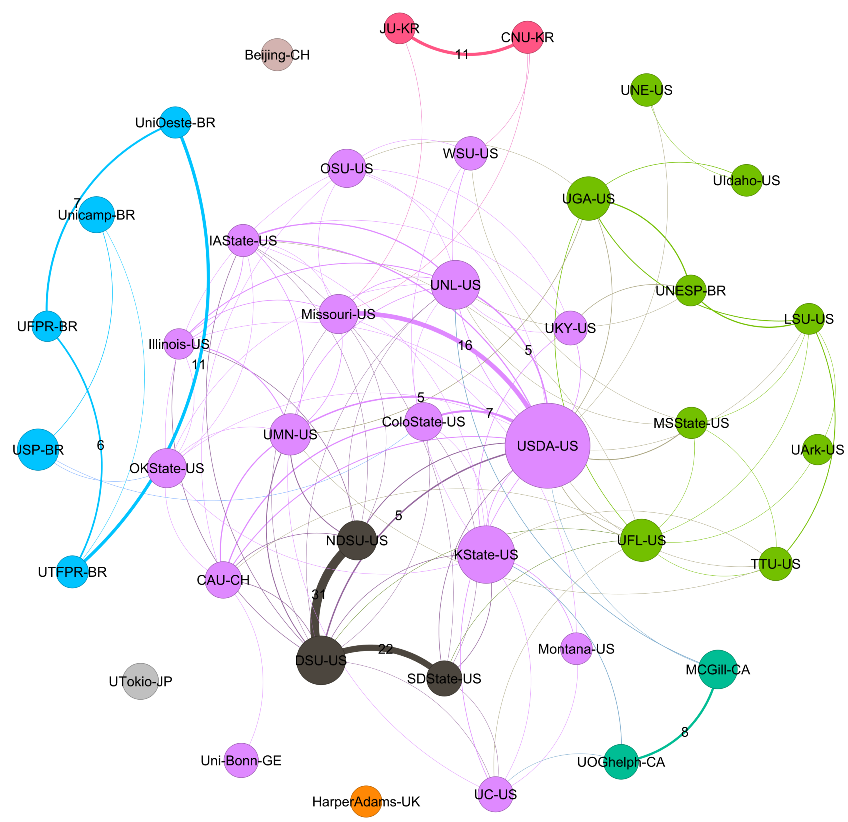

Fig 3. Top-ranked institutions and their respective collaboration networks within the ICPA co-authorship structure.

At the country level, the results confirm the global nature of the ICPA, with contributions distributed across multiple regions. However, the network is not uniformly balanced. A small number of countries dominate both in terms of productivity and centrality, indicating asymmetries in participation and influence. This concentration reflects broader structural inequalities in scientific research, including access to funding, infrastructure, and technological resources. At the same time, the presence of emerging contributors suggests a gradual diversification of the field.

Table 3. Top contries ranking.

Pos	Country	Pub	Deg	BC	PR	Com
1	USA	**730**	**30**	**0,387036**	**0,201747**	2
2	Brazil	157	8	0,021356	0,057143	2
3	Canada	111	12	0,024556	0,062351	2
4	China	93	5	0,002678	0,057748	2
5	Germany	83	13	0,083399	0,043509	4
6	Australia	42	8	0,042866	0,026238	2
7	Japan	36	2	0,024590	0,014596	4
8	Israel	27	3	0,000273	0,013852	2
9	India	27	2	0,000000	0,011485	2
10	South Korea	22	1	0,000000	0,005876	2
11	Belgium	21	6	0,010956	0,015441	5
12	New Zealand	21	1	0,000000	0,004803	2
13	Spain	20	8	0,038484	0,020807	4
14	Denmark	19	5	0,001939	0,015009	4
15	United Kingdom	17	5	0,003053	0,014169	2
16	Chile	16	4	0,005398	0,012873	2
17	Iran	15	3	0,001155	0,007795	5
18	France	14	11	0,044750	0,030380	5
19	Hungary	14	4	0,000000	0,011569	5
20	Sweden	14	2	0,000000	0,009985	2
21	Italy	12	9	0,016730	0,021084	5
22	Malaysia	12	5	0,093989	0,022588	4
23	Saudi Arabia	9	3	0,024590	0,012605	2
24	Finland	9	1	0,000000	0,004705	4
25	Austria	8	5	0,003775	0,013495	5
26	Ghana	8	4	0,000546	0,013490	5
27	Netherlands	8	1	0,000000	0,019627	2
28	Argentina	7	4	0,005398	0,011376	2
29	Poland	7	2	0,000000	0,010667	2
30	Czech Republic	7	0	0,000000	0,002944	
31	Colombia	6	0	0,000000	0,002944	
32	Mongolia	5	3	0,000000	0,012615	2
33	South Africa	5	2	0,000000	0,006562	5
34	Greece	5	2	0,000000	0,006171	4
35	Nigeria	5	0	0,000000	0,002944	

36	Oman	5	0	0,000000	0,002944

The Table 3 presents the most productive countries in the ICPA collaboration network, considering only those with participation in five or more publications. This filtering criterion ensures a focus on consistently active contributors, revealing a diverse set of countries spanning different regions and levels of scientific development. Among them, the USA clearly stands out with a substantially higher number of publications, followed by countries such as Brazil (2nd), Canada (3rd), China (4th), and Germany (5th), which also demonstrate significant research output and participation in the network.

In addition to leading in publication count, the USA achieves the highest values across all analyzed network metrics, including degree (Deg), betweenness centrality (BC), and PageRank (PR), confirming its dominant and central role in the global collaboration structure. Other countries, such as Germany (5th) and France (18th), show notable centrality values in specific metrics, indicating their importance as intermediaries or influential nodes within the network. Overall, the results highlight a highly interconnected international research landscape, with a clear concentration of influence in a few leading countries (Figure 4).

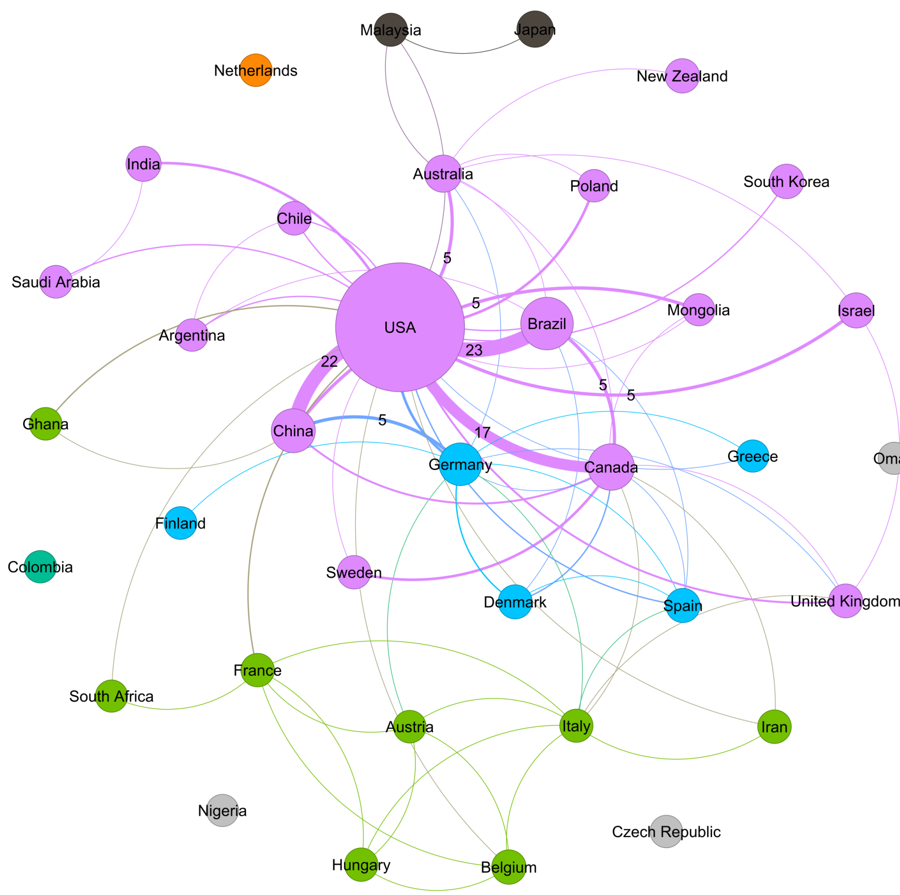

Fig 4. Countries and their respective collaboration networks within the ICPA co-authorship structure.

The dataset indicates participation from countries worldwide, including North and South America (e.g., Brazil, USA, Canada, Argentina, Chile, Colombia), Europe (e.g., United Kingdom, Germany, France, Spain, Italy, Netherlands, Denmark, Sweden, Finland, Austria, Belgium, Poland, Czech Republic, Greece, Hungary), Asia (e.g., China, India, Iran, Israel, Japan, Malaysia, Saudi Arabia, South Korea, Oman), Africa (e.g., South Africa, Ghana, Nigeria), and Oceania (Australia and New Zealand). This wide geographical distribution highlights the global relevance of precision agriculture technologies and their varied agricultural, climatic, and socio-economic contexts.

Community Structure and Collaboration Patterns

The application of the Louvain algorithm reveals a modular structure composed of distinct collaboration communities. These communities correspond to groups of authors, institutions, and countries that maintain stronger internal connections than external ones, reflecting shared research interests, long-term partnerships, or institutional affiliations (Figures 2, 3, and 4).

The modularity of the network indicates that, while the ICPA community is globally connected, it is not homogeneous. Instead, it is organized into semi-independent clusters that contribute to the overall structure of knowledge production. This configuration is typical of scientific fields where specialization and collaboration coexist, allowing for both depth within subdomains and connectivity across them.

Importantly, certain actors emerge as bridges between communities, as indicated by high betweenness centrality. These actors are critical for maintaining the cohesion of the network, as they enable the flow of information between otherwise disconnected groups. Their role suggests that the evolution of the ICPA community depends not only on the productivity of its members but also on the presence of intermediaries capable of linking different research domains.

Thematic Structure and Research Trends

The analysis of keyword co-occurrence networks reveals a thematic structure centered around core concepts such as precision agriculture, remote sensing, and machine learning (Table 4, Figure 5). These topics form the backbone of the field and are consistently present across the dataset, indicating their foundational role in the development of the discipline.

At the same time, the presence of more specialized and emerging keywords suggests an ongoing diversification of research topics. This expansion reflects the integration of new technologies and methodologies, as well as the adaptation of precision agriculture to different contexts and challenges. However, the coexistence of synonymous or closely related terms indicates a degree of semantic fragmentation, which may obscure the true structure of thematic relationships. This highlights the importance of keyword normalization in future studies.

Table 4. Top keywords ranking.

Pos	Keyword	Pub	Deg	BC	PR	Com
1	precision agriculture	**211**	**658**	**0,298968**	**0,022324**	2
2	remote sensing	126	394	0,133378	0,013125	1
3	machine learning	57	214	0,059955	0,006309	1
4	nitrogen	57	178	0,034147	0,005722	1
5	NDVI	52	200	0,040735	0,006196	1
6	UAV	48	169	0,024409	0,005114	1
7	corn	47	160	0,037225	0,004756	1
8	spatial variability	41	120	0,027584	0,003775	2
9	precision farming	37	134	0,037929	0,003979	1
10	management zones	34	93	0,017397	0,002777	2
11	wheat	32	108	0,017389	0,003021	1
12	GIS	30	101	0,019703	0,003188	15
13	deep learning	28	111	0,019349	0,003254	4
14	cotton	28	85	0,016557	0,002392	2

15	variable rate	26	92	0,016547	0,002678	1
16	yield	25	97	0,018400	0,002720	2
17	irrigation	22	66	0,016934	0,001935	1
18	variable rate application	22	65	0,013052	0,002047	2
19	maize	21	82	0,012513	0,002225	1
20	vegetation indices	21	64	0,006643	0,001964	1
21	proximal sensing	20	61	0,012837	0,001775	1
22	image processing	19	79	0,011104	0,002050	1
23	biomass	19	76	0,008180	0,002092	1
24	GPS	19	75	0,011047	0,002236	16
25	yield prediction	19	72	0,009925	0,001946	2
26	adoption	19	61	0,008628	0,001957	11
27	soil moisture	19	57	0,014956	0,001865	3
28	education	18	61	0,009707	0,002024	6
29	artificial intelligence	18	58	0,011868	0,001778	7
30	winter wheat	18	57	0,007844	0,001609	1
31	soybean	17	67	0,006672	0,001828	1
32	vegetation index	17	61	0,007880	0,001623	1
33	big data	16	71	0,008870	0,001998	2
34	UAS	16	59	0,005444	0,001575	1
35	machine vision	16	57	0,010579	0,001656	4
36	digital agriculture	15	56	0,011568	0,001577	11
37	soil	15	56	0,006522	0,001620	14

At the top of the ranking, “precision agriculture” clearly stands out as the central organizing concept of the field. It achieves the highest values across all evaluated metrics—number of publications (Pub = 211), degree (Deg = 658), betweenness centrality (BC = 0.298968), and PageRank (PR = 0.022324). This consistent dominance indicates that precision agriculture is not only the most frequent keyword but also the most influential and interconnected node in the network, acting as the main hub that bridges different research themes.

A second tier of highly relevant keywords is led by “remote sensing”, which presents strong performance across all metrics (Pub = 126; Deg = 394; BC = 0.133378; PR = 0.013125). Its high centrality values suggest that remote sensing technologies play a pivotal role in connecting multiple research areas, particularly those related to monitoring, data acquisition, and spatial analysis. Closely associated with this technological axis are terms such as NDVI, UAV, GIS, and proximal sensing, reinforcing the importance of geospatial and sensing technologies within the domain.

Another important cluster is formed by data-driven and artificial intelligence approaches, including machine learning, deep learning, artificial intelligence, big data, image processing, and machine vision. Among these, machine learning stands out with relatively high degree and centrality (Deg = 214; BC = 0.059955), indicating its strong integration with other topics such as yield prediction, crop monitoring, and decision-making systems. Although deep learning and artificial intelligence appear with lower frequencies, their presence among the top-ranked keywords reflects a growing trend toward advanced computational methods in recent years.

The agronomic and environmental dimension is also well represented. Keywords such as nitrogen, soil moisture, soil, and spatial variability indicate that understanding field heterogeneity and nutrient dynamics remains a central concern. Notably, nitrogen exhibits high frequency and connectivity (Pub = 57; Deg = 178), highlighting its relevance in studies focused on input optimization and sustainability.

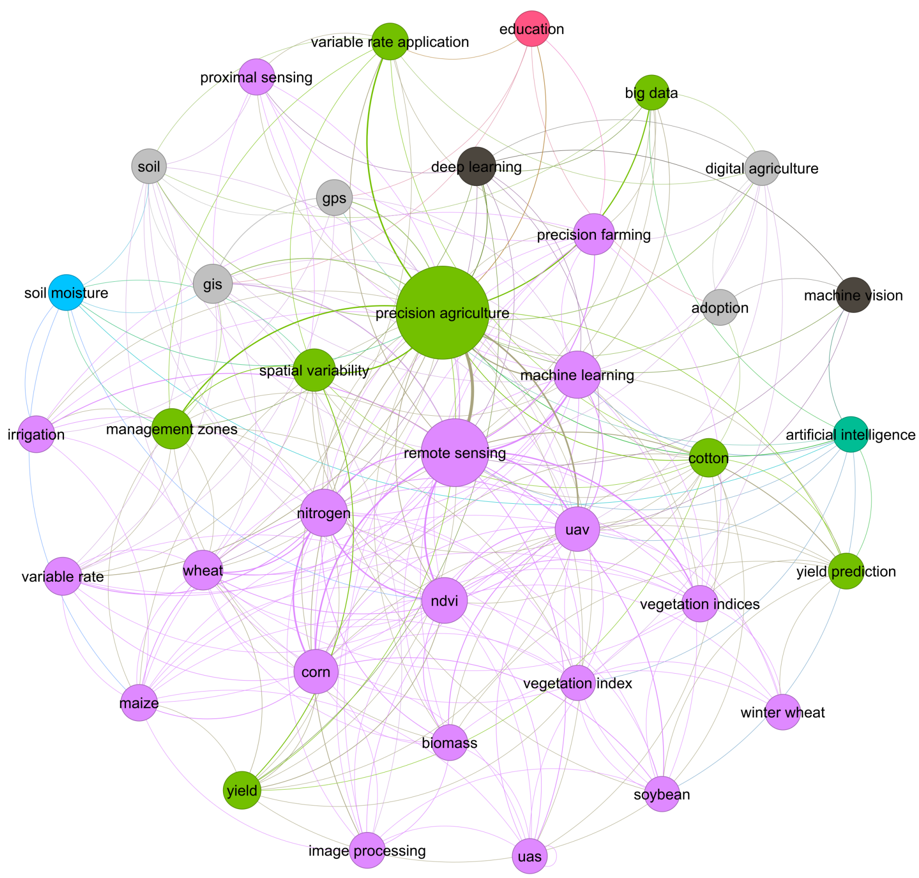

Fig 5. Most frequent keywords and their respective co-ocurrence networks within the ICPA history.

In parallel, a management-oriented cluster emerges, including variable rate, variable rate application, management zones, and irrigation. These terms are directly linked to the practical implementation of precision agriculture, translating data insights into actionable field operations. Their moderate centrality values suggest that they serve as bridges between sensing technologies and agronomic applications.

The dataset also shows a strong presence of crop-specific keywords, such as corn/maize, wheat/winter wheat, soybean, and cotton. Among these, corn and wheat are particularly prominent, indicating that research efforts are heavily concentrated on major commodity crops. These terms often co-occur with yield and yield prediction, emphasizing the production-oriented focus of the field.

Finally, less central but still meaningful are keywords related to adoption and education, such as adoption, education, and digital agriculture. Although these terms exhibit lower centrality and connectivity, their presence suggests an expanding interest in the socio-technical dimensions of precision agriculture, including knowledge transfer, training, and technology uptake.

In summary, the table highlights a core-periphery structure in which precision agriculture functions as the dominant hub, surrounded by interconnected clusters of sensing technologies, data science methods, agronomic variables, and management practices. This configuration reflects the inherently interdisciplinary nature of the field and underscores the increasing integration of digital technologies with traditional agricultural sciences.

Structural Implications and Evolution of the ICPA Community

Taken together, the results suggest that the ICPA has evolved into a structured yet dynamic scientific community. The presence of central actors and well-defined collaboration clusters indicates a level of maturity, while the persistence of peripheral nodes and emerging topics points to ongoing growth and diversification.

From a structural perspective, the coexistence of centralization and modularity appears to be a defining characteristic of the ICPA network. Central actors contribute to stability and continuity, whereas community structures enable specialization and innovation. The interaction between these elements shapes the dynamics of knowledge production within the conference.

Moreover, the observed patterns of collaboration and influence suggest that the development of precision agriculture as a scientific field is closely tied to the evolution of its research networks. Understanding these dynamics provides valuable insights into how knowledge is generated, disseminated, and consolidated within the community.

Limitations and Future Directions

Despite its contributions, this study has some limitations. The analysis is restricted to proceedings that are publicly available online, which may not fully represent the entire historical corpus of the ICPA. Additionally, potential inconsistencies in author names and institutional affiliations may affect the accuracy of network representations. The absence of citation-based analysis also limits the assessment of scientific impact beyond collaboration patterns.

Future research could address these limitations by incorporating citation networks, performing temporal analyses to capture the evolution of the community over time, and applying semantic normalization techniques to improve keyword analysis. Such extensions would provide a more comprehensive understanding of the development of precision agriculture research within the ICPA.

Conclusion

This study presented a comprehensive multi-scale analysis of the actors shaping the recent history of the International Conference on Precision Agriculture. By examining patterns at the levels of authors, institutions, countries, and keywords, the proposed framework enabled a structured understanding of how scientific collaboration and thematic evolution have unfolded within this research community.

The results highlight the presence of influential contributors and institutions that act as central nodes in the collaboration network, reinforcing the importance of established research hubs in driving innovation in precision agriculture. At the country level, the analysis revealed both dominant and emerging contributors, indicating a gradual diversification of the field and the increasing globalization of research efforts. Furthermore, the keyword analysis provided insights into the thematic trends of ICPA, identifying shifts in focus areas and the growing relevance of data-driven and technology-oriented approaches.

The multi-scale perspective adopted in this work proved effective in capturing the complexity of the scientific ecosystem, demonstrating that no single level of analysis is sufficient to fully understand the dynamics of knowledge production. Instead, the integration of multiple analytical layers allows for a more nuanced and holistic interpretation.

From a methodological standpoint, the proposed framework is scalable and adaptable, making it suitable for application to other scientific communities or domains. This is particularly relevant for supporting strategic decision-making, fostering collaboration, and identifying research gaps.

Future work may extend this analysis by incorporating additional data sources, such as citation networks or funding information, as well as applying longitudinal models to better capture temporal dynamics. Moreover, qualitative analyses could complement the quantitative findings, providing deeper insights into the contextual factors influencing collaboration and research trends.

In summary, this study contributes to a better understanding of the structure and evolution of the precision agriculture research community and provides a robust analytical approach for exploring complex scientific landscapes.

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