Agricultural Systems 219 (2024) 104013

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

What traits of collaboration networks are associated with project success? The case of two CGIAR agricultural research programs for development

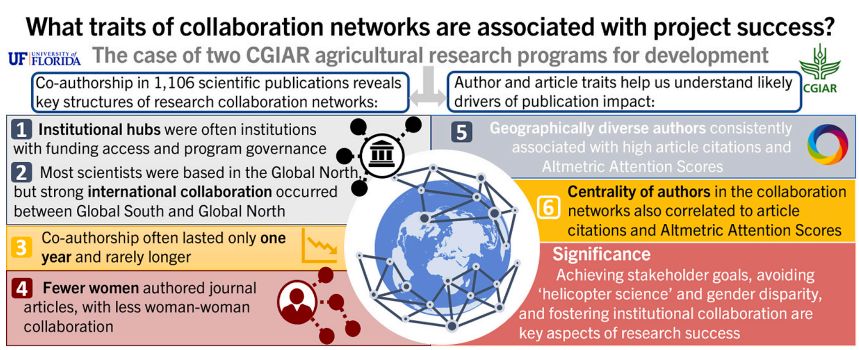
Aaron I. Plex Sulá [a,b,*], Valentina De Col [c], Berea A. Etherton [a,b], Yanru Xing [a,b], Amogh Agarwal [a,b], Lejla Ramić [a,b], Enrico Bonaiuti [c,d], Michael Friedmann [d], Claudio Proietti [e], Graham Thiele [d], Karen A. Garrett [a,b,*]

[a] Global Food Systems Institute, University of Florida, Gainesville, FL, USA
[b] Plant Pathology Department, University of Florida, Gainesville, FL, USA
[c] International Center for Agricultural Research in Dry Areas (ICARDA), Beirut, Lebanon
[d] International Potato Center (CIP), Lima, Peru
[e] French Agricultural Research Centre for International Development (CIRAD), Montpellier, France

HIGHLIGHTS

- The structure and impact of collaboration networks in agriculture for development are key to research success.
- We apply a new framework for evaluating the success of collaboration networks to two global research programs of the CGIAR.
- Publications had strong international and institutional collaboration but less than a third of authors were women.
- Publication traits such as geographically diverse author affiliations were associated with more citations.
- These findings about scientific capacities and gaps support steps to research success in agricultural development.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Dr. Laurens Klerkx

Keywords:
Knowledge management
Network analysis
Science of science
Science mapping
Successful research networks
Web of Science
Agricultural innovation

ABSTRACT

CONTEXT: Understanding research collaboration in diverse scientific communities is key to building global agricultural research systems that support the UN Sustainable Development Goals. Characterizing collaboration patterns can inform decisions to enhance the structure and dynamics of research programs.

OBJECTIVE: We introduce a new analytic framework for evaluating collaborative research networks based on scientific publications, and an associated conceptual framework for the role of research networks in achieving societal goals. We analyzed two CGIAR Research Programs: Grain Legumes and Dryland Cereals (GLDC) and Roots, Tubers and Bananas (RTB). The analysis provides a multi-dimensional perspective on a set of key questions related to research team composition, research management structures, and performance of scientific publications.

* Corresponding authors at: Global Food Systems Institute, University of Florida, Gainesville, FL, USA.
E-mail addresses: plexaaron@ufl.edu (A.I. Plex Sulá), v.decol@cgiar.org (V. De Col), betherton@ufl.edu (B.A. Etherton), amoghagarwal@ufl.edu (A. Agarwal), lejla.ramic8@gmail.com (L. Ramić), e.bonaiuti@cgiar.org (E. Bonaiuti), mfried005@outlook.com (M. Friedmann), claudio.proietti@cirad.fr (C. Proietti), g.thiele@cgiar.org (G. Thiele), karengarrett@ufl.edu (K.A. Garrett).

https://doi.org/10.1016/j.agsy.2024.104013
Received 30 May 2023; Received in revised form 29 April 2024; Accepted 24 May 2024
Available online 15 June 2024
0308-521X/

METHODS: We quantified network structures of research collaborations at the level of authors, institutions, countries, and management structures, including use of temporal exponential random graph models. We used regression models to understand the associations between the characteristics of authors and publications, and the corresponding citation rates and Altmetric Attention Scores.

RESULTS AND CONCLUSIONS: We identified key network hubs in the collaboration networks of both CGIAR programs. The proportion of women as authors in publications was less than a third, with a low likelihood of co-authorship between women. Institutional hubs were identified by institutional categories; these were often institutions that are considered CGIAR program "participants", and a few were "planning partners". For both GLDC and RTB, the countries that were the focus of most research coincided with the program's priority countries. Most international collaborations occurred between institutions headquartered in Global South countries, but most intercontinental collaborations occurred between Global South and Global North countries. Most institution and author co-authorships occurred in only one year and rarely lasted two or three consecutive years. High diversity in the geographic affiliations of authors, along with highly collaborative teams, as opposed to simply the number of authors, consistently were associated with more citations and higher Altmetric Attention Scores.

SIGNIFICANCE: These analyses reveal key structures in research collaboration networks in GLDC and RTB research programs, with potential to guide agricultural research systems for sustainable development. Considering these outcomes from past research management can help scientists, program managers, and funders increase the success of new research projects. Specifically, future research management strategies need to fortify existing scientific capacity and development through gender parity and balanced international collaborations, working toward more impactful publications and increased development relevance, while team size increases over time.

1. Introduction

1.1. Research collaboration structures in agricultural innovation systems

Agricultural research for development is at the interface of science, education, and industry, from crop breeding for improved varieties (Byerlee and Dubin, 2009; Garrett et al., 2017) to the establishment of effective seed systems (McEwan et al., 2021). In agriculture as in other sciences, collaboration drives the development, integration and spread of concepts, policies, and technologies (Fortunato et al., 2018; Miao et al., 2022). Interdisciplinary systems are needed to improve agroecosystems and achieve the UN Sustainable Development Goals, in the face of multifaceted problems like climate change, continental epidemics, and social inequalities. Understanding the structure of recent collaboration networks, and how these structures are associated with research success, is a key component for building agricultural innovation systems that support effective research (Klerkx and Begemann, 2020) and a first step toward developing sustainable strategies for achieving societal goals (Fortunato et al., 2018; Miao et al., 2022). Two overarching goals of this paper are to provide (a) a new conceptual framework for how research networks fit in larger agricultural innovation networks, and (b) a new analytic framework for understanding collaboration networks in agricultural research, the science of agricultural science.

Network analysis provides an important perspective on the structure of research collaboration. Effective collaboration often depends on networks of interinstitutional and international participation, and the engagement of authors representing different types of stakeholders, such as different genders (Adams, 2012; Katz and Martin, 1997; Maru et al., 2018). Network analysis can identify the roles of people, institutions, and countries in research collaboration networks (Bettencourt et al., 2009; Miao et al., 2022). A network-based approach also supports comparing a priori expectations about organizational structures with observed research collaboration networks, and tracing spatiotemporal dynamics of research collaboration across scientific communities. The new analytic framework we present here is designed for evaluating research networks in agriculture development (Table 1). We apply this framework to two research programs in CGIAR.

CGIAR, formerly the Consultative Group on International Agricultural Research, is the world's largest global agricultural research and innovation network, providing evidence to policy makers, supporting innovation by partners, and making available new tools for the economic, environmental, and nutritional sustainability of agriculture (CGIAR System Organization, 2021). CGIAR programs span a wide range of approaches to agricultural research for development conducted primarily by 15 international agricultural research centers, contributing to many targets in the global resource sustainability agenda, and providing a unique opportunity for testing our network-based framework. We evaluated two multi-crop CGIAR Research Programs (CRPs): Grain Legumes and Dryland Cereals (GLDC) and Roots, Tubers and Bananas (RTB; Box S1 provides more information about the CGIAR and the GLDC and RTB Programs). Analysis of CGIAR research structures is particularly important now as CGIAR transitions into the new One CGIAR program. A major rationale for the One CGIAR reform was to develop more integration across CGIAR centers and partners as an effective system (Byerlee and Lynam, 2020). CGIAR's role includes building effective collaboration networks, to provide critical mass and expertise from advanced research institutions as well as strengthening national programs in low- and lower-income countries (Barrett, 2020).

Agricultural innovation systems include research collaboration networks as a part of the much broader network of stakeholders. The new conceptual framework we present (Fig. 1) includes basic research project traits (such as funding level), collaboration network traits (such as international partnerships), and the broader outcomes the system is intended to produce (such as improved farmer livelihoods). It is important to keep this more complete system in mind, even though any given project is likely to be limited to a piece of the broader system (Reardon et al., 2019). The goals, or missions, of mission-oriented agricultural innovation systems may develop as a result of pushes from science, policy, or business, or as pulls from social movements and consumers (Klerkx and Begemann, 2020). Integrated agricultural research for development (IAR4D) emphasizes that stakeholders throughout the value chain should be engaged, as opposed to research simply driven by scientists and distributed by extension (Maru et al., 2018).

Our objectives in this study are, first, to use network analysis to quantify research collaboration based on the scientific papers published by GLDC and RTB during part of their Phase II through 2020. Second, we apply the new analytic framework, addressing a set of important questions for stakeholders who have the responsibility to guide agricultural research for development (Table 1), targeting key aspects of research team composition (National Research Council, 2015), structural research management, and performance of scientific publications. These questions are already widely (yet separately) studied in scientific disciplines such as ecology, medicine, and economics (Huang et al., 2020; Minasny et al., 2020; Petersen, 2015). These questions are rarely

Table 1
Framework of questions and hypotheses about co-authorship networks that is applied here to co-authorship networks of two CGIAR research programs: Grain Legumes and Dryland Cereals (GLDC) and Roots, Tubers and Bananas (RTB).

Question	General hypothesis or a priori expectation	Network analysis
A. Research system diversity and structure		
A1. To what extent do researchers collaborate with others within their own group, in terms of institution, country, and gender?	There will be homophily in each type of group (Boschma, 2005).	Homophily testing using temporal exponential-family random graph models (TERGMs)
A2. Are there institutions or individual scientists that play key roles in the research collaboration network?	Key nodes will act as network hubs and bridges due to the phenomenon of preferential attachment in research collaboration networks (Bettencourt et al., 2009).	Quantification of node centralities in the co-authorship networks, such as node degree and betweenness centrality
A3. How much research is conducted in the country where authors are affiliated, versus internationally?	There will be a greater share of research outside authors' countries, typically having international teams that include local scientists (Rees et al., 2021).	Geographic analysis of research collaboration networks
A4. What are the differences in the role of countries in the Global South versus Global North?	There will be few cases of research conducted in the Global South that did not include scientists located in the Global South (Dahdouh-Guebas et al., 2003; Minasny et al., 2020).	Geographic analysis of research collaboration networks
B. Changes in research systems across time		
B1. Did co-authorship teams increase in size over time?	Co-authorship team size would increase across years (Larivière et al., 2015; Wu et al., 2019).	Analysis of annual changes in team size
B2. Did the networks expand over time, in terms of authors and institutions?	The number of authors in each CRP will increase over time (Larivière et al., 2015; Wuchty et al., 2007).	Temporal analysis of collaboration network size
B3. Are long-term partnerships established?	Partnerships in co-authored publications will usually last few years (Petersen, 2015).	Analysis of link duration in the research collaboration network
C. Research system management structure		
C1. What are the roles in the network of projects within a CRP (e.g., Flagships) compared to ones resulting from bilateral projects?	Institutional collaboration will tend to disaggregate based on participation of Flagships.	Comparison of CRP Flagships and bilateral projects
D. Research system performance		
D1. What co-authorship group and article traits are associated with citation numbers or Altmetric Attention Scores?	Variables associated with team size (number of authors) will frequently drive the citation and Altmetric Attention Scores of scientific publications (Larivière et al., 2015).	Bibliometric analysis of article and author characteristics

assessed quantitatively and lack a unifying framework for large-scale research networks in food and agricultural sciences. Our proposed framework builds on a multidimensional perspective on research success (Fig. 1), including understanding how key traits or structures of collaboration networks might influence research outcomes, and potentially guiding policies in public organizations like CGIAR. Research success is a multidimensional process involving, for example, outcomes for stakeholders, predefined management targets, and social goals. Likewise, project traits may contribute to multiple types of research success over different timescales. In this study, we address several of the key components for research success, providing a baseline for future studies that will build on information that is currently unavailable and incorporate more dimensions of project traits and outcomes (Maru et al., 2018).

1.2. Team science in agricultural research

In our analyses of the GLDC and RTB collaboration networks, we evaluate a set of questions and expectations about research networks developed in the science of team science (Milojevic, 2014). Author traits and publication traits are elements of larger collaboration system traits, such as the collaboration network structure and research program priorities. The resulting team structure can drive the likelihood of a project's performance and influence (Larivière et al., 2015; Wu et al., 2019). Our first question (Question A1 in Table 1) is about research homophily, i.e., whether researchers tend to collaborate with other researchers who are within the same group (Boschma, 2005; Olechnicka et al., 2019), in terms of gender, country and institution. Our expectation is that there will be a tendency toward collaboration homophily. Gender parity is a UN Sustainable Development Goal (SDG5), and a social dimension of research success, improving scientific collaboration because the perspectives of different gender categories can improve research productivity and boost engagement (Zeng et al., 2016). To contribute to IAR4D, a balanced gender engagement may help make research products more accessible for female farmers, female researchers, and other female stakeholders throughout the agricultural value chain (Maru et al., 2018; Quisumbing et al., 2014). We also expect that there will be key research agents, such as institutions and individual scientists (Question A2), who play a role as network hubs (agents collaborating with many others) and bridges (agents linking across parts of the network that otherwise might be separate).

We assess a program's research in terms of whether it is conducted in the country of the affiliated authors versus in other countries (Question A3). A balanced inclusion of local scientists is important to successfully reduce inequalities (SDG10) by avoiding 'neocolonial science' or 'helicopter research,' in which researchers from the 'Global North' (i.e., high-income countries) collect data and publish papers without co-authoring with local scientists in the 'Global South' (i.e., low- and middle-income countries) (Dahdouh-Guebas et al., 2003; Minasny et al., 2020). Our expectation for international collaboration in CGIAR is that there will be few cases of research without local scientists, and instead research will typically involve international teams that include local scientists. The geographic distribution of the international research community can enhance the exchange of agricultural expertise and use of technologies among countries (Olechnicka et al., 2019). We also assess the roles of researchers in countries in the Global South and North (Question A4) since collaboration between these two types of countries also helps avoid helicopter research (Adams, 2012). Because GLDC and RTB prioritize research on arid, semi-arid, and tropical agriculture, an expected positive outcome would be that more researchers are affiliated with countries in the Global South than researchers affiliated with countries in the Global North, and that researchers in the Global North focus on studies in the Global South.

Changes in a research system across time indicate the effects of a program combined with overall trends in research communities. Since the 1960s, in many scientific fields there has been a global increase in research team size, scientific publications, co-authorship (number of authors per paper) and research collaboration (e.g., institutions per paper) (Broad, 1981; Larivière et al., 2015; Milojevic, 2014; Wuchty et al., 2007). Our expectation is that research for development in GLDC and RTB will show a similar trend of increasing size of co-authorship teams (Questions B1–3). Strategic partnerships at multiple levels

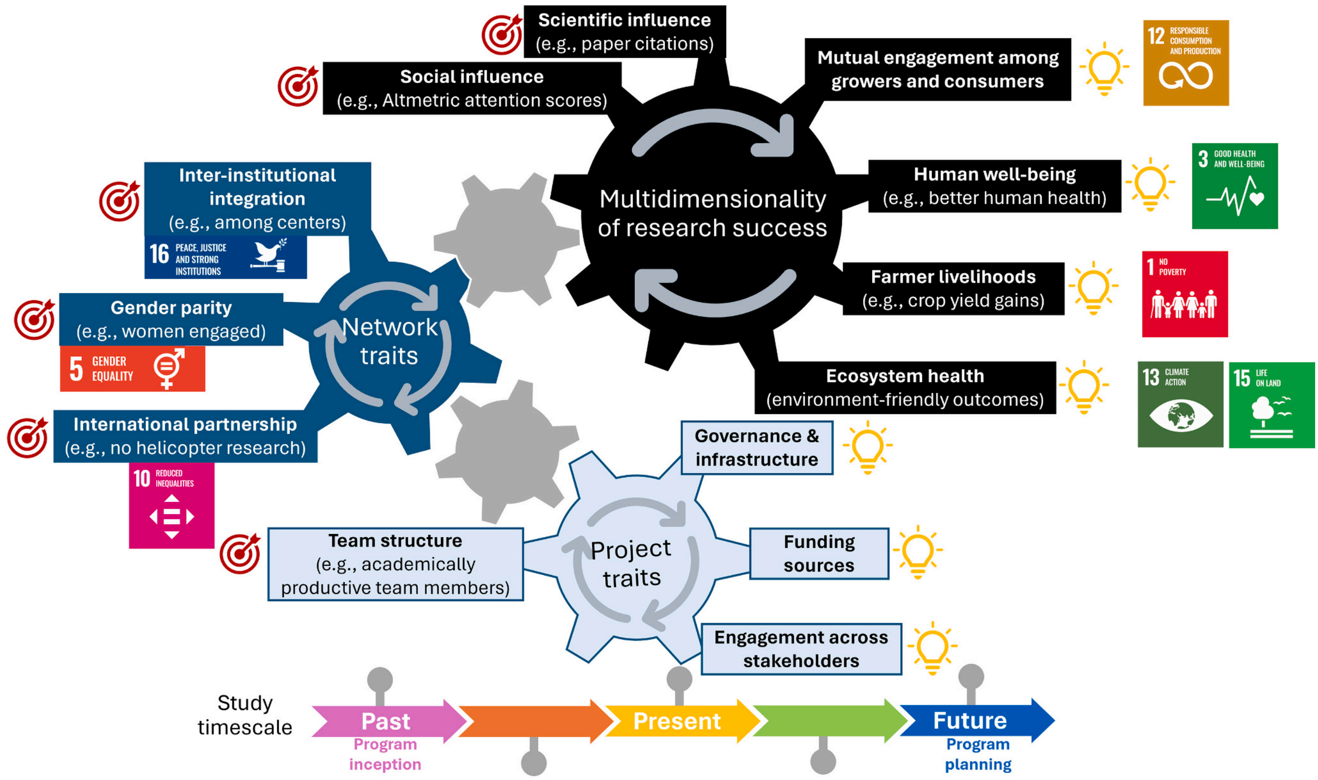


Fig. 1. A framework for evaluating the role of research collaboration networks in larger agricultural innovation systems to support the UN Sustainable Development goals. This new framework highlights the multidimensional perspective needed to build effective operating systems in global agricultural research for development. In this framework, (i) general project traits (light blue gear), such as multi-sourced funding and governance, are major engines in empowering research programs and setting research priorities, (ii) some research network traits can be a type of success in themselves (dark blue gear), and also are likely to contribute to larger-scale success, and (iii) available indices are used as approximations to measure the actual performance of research programs, in terms of success among researchers and success in broader societal goals (dark gear). Our study is a network-based assessment focused on a subset of these project dimensions (target icons), while future studies can build on this baseline to fill information gaps for other system aspects that require longer-term assessment or are challenging to measure (light bulb icons). This study provides evidence for the dynamics of some project success dimensions over a multi-year snapshot, and the proposed conceptual and analytical frameworks can be used for evaluating the evolution of research success over longer timescales, in retrospect or for planning prospective research strategies across decades. Symbols associated with system components are from the UN Sustainable Development Goals.

(institutions, scientists, or countries) contribute to SDG16. Our findings illustrate how partnerships in GLDC and RTB strengthen the global anchoring role of CGIAR as 'an exemplary node in larger networks' (Barrett, 2020), and how centers integrate into a coordinated system operating on a spectrum of food crops with spatially dispersed national partners (Byerlee and Lynam, 2020).

Evaluating research outputs as a function of the organizational structure of research programs is an important first step to support effective decision-making and inform future research for development investments. Within each CRP there were four levels of research management (with details in Box S1). We evaluated the role of the management groups termed Flagships and Clusters of Activities – the first and second level of research management – in the research collaboration networks of institutions (Question C1).

We also used bibliometric analysis to understand which factors are likely driving the performance of scientific articles published by both CRPs (Question D1). We assess the relative roles of article and author characteristics in the performance of scientific publications, where our proxies for success were the number of citations and Altmetric Attention Scores (Fig. 1). Bibliometric analyses provide an important point of departure for identifying which variables likely play important roles in the impact of agricultural science (Akella et al., 2021; Tahamtan et al., 2016). This study addresses the linked set of questions introduced above (Table 1), harnessing both bibliometric and network analyses. These multicriteria analyses are complementary and enable us to quantitatively understand the implementation of agricultural research collaborations in GLDC and RTB.

2. Materials and methods

2.1. Data collection

The dataset analyzed in this study collates the scientific production of two CRPs, GLDC and RTB, during their Phase II (Box S1). This study included publications from a shorter period (01/01/2018–31/12/2020) for GLDC and a period one year longer (01/01/2017–31/12/2020) for RTB, which started its research program earlier. This dataset is an extensive data compilation about peer-reviewed journal articles reported by both CRPs in their respective Annual Reports (https://www.cgiar.org/food-security-impact/results-dashboard/) and integrates data and metadata from the CGIAR Monitoring, Evaluation and Learning (MEL) platform (https://mel.cgiar.org/), Web of Science (WoS) (https://clarivate.com/webofsciencegroup/), Scopus (https://www.elsevier.com/solutions/scopus), Unpaywall (https://unpaywall.org/), Altmetrics (https://www.altmetric.com/) and Gender Application Programming Interface (Gender API, https://gender-api.com/). We obtained the list of journal articles from the GLDC and RTB annual reports and validated this dataset by retrieving data and metadata using the digital object identifier (DOI) of each article and the MEL Quality Assurance Processor publications metadata extractor (https://qap.mel.cgiar.org/qa/qap). For publications without a DOI, metadata were manually curated following the General Dataset Curation Guide (Bonechi et al., 2019).

2.2. Network analysis and visualization

We used network analysis to address key questions about collaboration and its outcomes (Table 1 and Table S1). Both GLDC and RTB are programs focusing on research for multiple crops and conducted by multiple centers. We analyzed GLDC and RTB separately because they differed in timing of Phase II, funding budgets for research and publications, allocation of indirect research costs, research infrastructure, number of scientists conducting research, and data availability (Immonen and Cooksy, 2019; Rünzel et al., 2021). We evaluated the articles published during the initial part of the CRPs' Phase II, over the first three of four years for GLDC and the first four of five years for RTB. Because the Alliance of Bioversity International and the International Center for Tropical Agriculture (CIAT) was established in 2019, we considered the authors' affiliations with the Alliance as two separate entities: Bioversity International and CIAT. We used the R programming environment (R Core Team, 2022) for analyses. Network visualizations were built using the R package ggraph (Lin Pedersen, 2021). The ggplot2 v3.3.6 package in R v4.2.0 was used for other visualizations (Wickham, 2016) and igraph v1.3.1 (Csárdi and Nepusz, 2006) was used to transform adjacency matrices into graph objects and to calculate network metrics.

2.3. Research system diversity and structure

2.3.1. Questions A1-A2. Research collaboration networks within a CRP

We first analyzed the structure of research collaboration networks in terms of 1) authors' institutions, 2) authors' countries of affiliation, 3) countries that were the subject of research, and 4) authors' gender.

2.3.2. Institution collaboration networks

We evaluated research networks of institutions collaborating in a CRP, where links between institution nodes indicated that authors affiliated with each of the institutions published scientific journal articles together. We measured the importance of each research institution as a potential hub based on the total number of collaborations (institution node degree), and the importance as a potential bridge between different parts of networks based on betweenness centrality (institution node betweenness). Each CRP had a different set of international research centers. We also evaluated the collaboration degree of 12 of these international research centers considered program participants (a complete list of these organizations is available in Table S2), which were characterized by being autonomous institutions with their own governing board (Immonen and Cooksy, 2019). We also assessed the collaboration degree of the following three distinct categories of institutions. (1) 'Participants' are institutions participating in the CGIAR Research Programs with access to funding and participation in CRP governance. (2) 'Planning partners' are institutions or centers added in the CGIAR MEL platform in the planning phase who receive one of three different types of funding: Window 1 (W1, portfolio investment used as determined by CGIAR System Council), Window 2 (W2, program investment directed by CGIAR donors to specific CRPs), Window 3 (W3, program investment directed by CGIAR donors to specific Centers and mapped by those Centers to the CRP) or bilateral funding (funding negotiated between donors and participants outside the CRP framework but still mapped by those participants to the CRP). (3) 'Collaborators' are other institutions or centers that contribute to conducting research and publishing journal articles but do not receive funding from the CRP or Center. Thus, a positive outcome would be that participants have higher node degree than planning partners or collaborators in these collaboration networks. We evaluated the formation and persistence of links between institutions (institutional collaborations) over time in terms of homophily between these three institution categories. To evaluate institutional homophily, we constructed a temporal exponential-family random graph model (TERGM) for each CRP using the tergm package v4.2.0 (Krivitsky and Handcock, 2023). In each TERGM, an annual series of institutional collaboration networks represented the 'response', link formation and link persistence were the operator terms, and edges and institutional homophily were the model terms for each operator.

2.3.3. Country collaboration networks

We analyzed collaborations between scientists' countries of affiliation and countries that were the focus of research, for the journal articles for which this information was available. The country of affiliation is often reported as the headquarters of authors' institutions, which may not correspond to the actual location of the author. In these networks, nodes represent two types of countries: where research was conducted (research-focus country) and where scientists were affiliated (country of affiliation). Links are directed from a country of affiliation of collaborating scientists to each country where the corresponding research was conducted. Link weights indicated the total number of collaborations between these two types of countries. We used node out-strength (sum of out-going link weights) and in-strength (sum of in-coming link weights) to assess the potential importance of each country in research collaboration networks. Affiliation countries with high out-strength collaborate with many research-focus countries, likely playing central roles in developing agricultural research, and spreading science across geographic collaboration networks. Research-focus countries with high in-strength may benefit from diverse and frequent international collaborations. CGIAR often emphasizes agricultural research in countries defined as priority countries at the planning stage of each CRP. We evaluated whether research-focus countries with high in-strength coincided with these priority countries.

2.3.4. Gender and co-authorship networks

We evaluated the structure of co-authorship networks in which nodes represent individual authors, and link weights represent the total number of co-authored papers between two individuals. Author gender was inferred from authors' names using the Gender API, which provided gender assignments for authors as male or female and a confidence parameter indicating the reliability of the assignment (Santamaría and Mihaljević, 2018). If the assignment had a confidence $<50\%$, gender was labeled as unknown. Many authors' first names were abbreviated to only the first letter, so 8.8% of the authors' genders could not be inferred.

We calculated probabilities of male-male (mm), male-female (mf), and female-female (ff) co-authorship and the rate of gender collaboration across CRP Phase II. For example, there are 6 males and 5 females who coauthored our paper, so there are 15 mm links, 10 ff links and 30 mf links. Based on Bayes' theorem, we evaluated the conditional probability of each of these types of links. The total number of authors of each gender was summed, excluding authors with no gender assignments from the analysis. We then calculated the probability of a link type occurring: $\mathrm{P(link\ type|gender)} = \frac{\mathrm{P(gender|link\ type)*P(link\ type)}}{\mathrm{P(gender)}}$. The probability of a specific link type occurring is equal to the ratio of a specific link type to all other link types, and the probability of an author being a specific gender is equal to the gender proportion.

We used two network metrics (node degree and betweenness centrality) to evaluate likely influences of authors in collaboration networks. To evaluate the evolution of co-authorship, we built a TERGM for each CRP with the annual series of co-authorship networks as the response, link formation and link persistence as operator terms, and edges and gender homophily as the model terms for each operator.

2.3.5. Questions A3-A4. International research collaboration performance

We evaluated whether research collaboration producing articles about research-focus countries was conducted locally or internationally. We categorized research as 'local' when the country of affiliation of at least one author was the same as the research-focus country. Using the country collaboration networks described in section A1-A2, for each pair of countries we compared the geographic proximity (Vincenty ellipsoid distance between country centroids) and the strength of collaboration (represented by link weights).

For each country collaboration network, we also classified each link as one of four collaboration categories based on whether countries of affiliation and research focus involved in the research collaborations are considered part of the Global North or Global South (Table S3 provides the complete characteristics of each link type). The attribution of a country node to either Global North or Global South was based on the historical classification of developed and developing regions by the Statistics Division of the UN Secretariat (standard country or area codes for statistical use, commonly referred to as the M49 standard, as of December 2021). “Developed” regions were assigned to the Global North, and “developing” regions to the Global South.

To compare collaboration between Global South and Global North countries in more detail, we evaluated each collaboration category across a network in two ways: a) summing the number of links in each category and b) summing the link weights in each category. We constructed two-by-two contingency tables to assess whether, for these collaboration frequencies, the number of author affiliation countries is associated with the number of research-focus countries, using a chi-square test, and comparing the resulting *p*-values with outcomes from Fisher’s exact test.

2.4. Research collaboration evolution

2.4.1. Questions B1-B2. Evolution of research during Phase II

In this section, we evaluated annual changes in several aspects of article publications (with details in Table S4 and summary in Table 2). Briefly, these aspects included the number of journal articles published, open accessibility, number of authors by gender and citations received by articles.

2.4.2. Question B3. Collaboration persistence

We assessed the persistence of dyadic (two-author or two-institution) research collaboration over time. For articles with more than one author, we constructed annual co-authorship research networks. In a matrix with rows representing each dyad collaboration and columns representing publication year, we evaluated whether each dyad collaboration occurred in each year (entries in the matrix assigned 1) or not (0). Our measure of collaboration persistence was the number of years each dyad collaboration occurred. For research collaboration networks of authors’ institutions, we measured the persistence of institutional collaboration using the same method.

Table 2
Summary of research collaboration in two CGIAR Research Programs (CRPs) on Grain Legumes and Dryland Cereals (GLDC) starting in 2018 and Roots, Tubers and Bananas (RTB) starting in 2017, during their Phase II through 2020. WoS refers to the Web of Science Core Collection.

Variables	CRP	Year			
		2017	2018	2019	2020
Number of journal articles	RTB	125	145	145	246
	GLDC	–	153	79	122
Number of journal articles in WoS	RTB	109	133	140	231
	GLDC	–	122	71	112
Proportion of journal articles in WoS	RTB	0.87	0.91	0.97	0.94
	GLDC	–	0.80	0.90	0.92
Number of open access journal articles	RTB	103	114	122	220
	GLDC	–	136	69	113
Proportion of open access articles	RTB	0.82	0.79	0.84	0.89
	GLDC	–	0.89	0.87	0.92
Total number of authors	RTB	663	1028	800	1227
	GLDC	–	853	567	909
Number of inferred men as authors	RTB	401	619	509	774
	GLDC	–	607	395	598
Number of inferred women as authors	RTB	169	289	223	392
	GLDC	–	168	119	219
Mean article team size	RTB	8.24	11.12	9.05	10.03
	GLDC	–	8.86	10.82	11.85
Mean number of article citations in WoS	RTB	14.12	11.5	8.31	3.02
	GLDC	–	9.57	11.57	5.13
Total number of citations in WoS	RTB	1765	1667	1205	745
	GLDC	–	1464	914	626

2.5. Research system management structure

2.5.1. Question C1. CGIAR management structures in research collaboration networks

Because research management structures, such as Flagships and Clusters of Activities, are important for understanding collaboration in CGIAR, we assessed research collaboration networks emphasizing the participation of Flagships. In these networks, one type of nodes represents Flagships, and the other type of nodes represents institutions with which authors are affiliated. Links represent the presence of collaboration between research institutions and Flagship programs. The relative importance of research collaboration in these networks was quantified in terms of node degree (the number of links by node).

2.6. Research system performance

2.6.1. Question D1. Article publication performance

We used two common article-level metrics as quantitative proxies for the research impact of articles (Akella et al., 2021; Fortunato et al., 2018; Tahamtan et al., 2016; Thelwall et al., 2013): times cited in the WoS Core Collection (hereafter WoS citations) and the journal article Altmetric Attention Score from Altmetrics (or Altmetric score). We assessed the association of 13 numeric explanatory variables extracted from journal article metadata with these impact metrics (Table 3). Because multiple aspects can influence the number of citations or attention score an article can obtain (Tahamtan et al., 2016), we evaluated only the relative potential importance of this set of explanatory variables.

Because our dataset represents approximately a complete ‘census’ of research articles from GLDC and RTB, it can be argued that statistical analyses are not needed to infer associations. Instead, we used statistical analyses to measure the strength of relationships compared to the variability in the system and assumed that any observed associations are ‘correct’ for the publications in these years. We fitted linear regression models with each impact metric as a response variable, using the R package mlr v.2.19.0 (Bischl et al., 2016). We imputed missing data for predictor variables using a regression algorithm: rpart decision tree, following the methods described by Rhys (2020). We excluded journal articles with missing values in impact metrics. We evaluated the likely importance of each predictor variable in WoS citations and Altmetric Attention Scores using feature selection based on random forest importance and Pearson correlation coefficients.

We cross-validated our models by selecting the best-performing features using the 13 variables and a 3-fold grid search with 10 iterations and selecting those models with the lowest mean square errors (MSE). We verified the following criteria for linear regression models: homoscedasticity, normally distributed errors, and linear relationships between variables (Rhys, 2020). We assessed multicollinearity between each pair of explanatory variables, using both pairwise Pearson correlation coefficients and variance inflation factors (VIF). Team size was correlated with geographic team diversity and institutional diversity. Activity diversity was correlated with Flagship diversity. Women as co-authors was correlated with team size and institutional diversity. The high association between these explanatory variables was also supported by VIF > 10, indicating that a large portion of these explanatory variables can be explained by the other variables in the dataset. We then built multiple regression models considering only nine explanatory variables, substituting explanatory variables showing both high Pearson correlation (usually >0.5) and VIF > 10 to minimize multicollinearity.

We first assessed a model (model 1) considering log(Altmetric

Table 3

Description of explanatory variables considered in a model to evaluate the performance of articles based on citations (from the Web of Science Core Collection) and Altmetric Attention Scores.

Explanatory variable	Description
Year of publication	The year when a publication appeared as published online.
Team size	The total number of co-authors of an article.
Institutional diversity	The total number of institutions collaborating in an article based on authors' affiliation(s).
Geographic team diversity	The total number of countries of affiliation associated with authors in an article.
Helicopter index	The number of non-local authors divided by the team size of an article. Non-local authors are those scientists affiliated with institutions located outside the region that was the research focus of an article.
Local collaboration	The number of local authors in an article based on the country of affiliation as reported in the article.
Women co-authors	The number of women co-authoring an article. We only considered women as those identified as females by the Gender API (details provided in the Methods section).
Gender index	For each article, the number of women authors divided by the total number of authors with a confident inferred gender category.
Research area diversity	The number of research areas as reported by the Web of Science for each article.
Geographic focus of research (or focus country diversity)	The number of research-focus countries where research was conducted. This information was manually curated and derived from the article's title, abstract, keywords, or full text (when open access).
Commodity diversity	The number of crop commodities (usually different crop species) addressed in an article. This information was manually curated and derived from the article's title, abstract, keywords, or full text (when open access).
Flagship diversity	The number of different CRP Flagships that reported the same article in MEL.
Activity diversity	The number of different CRP Clusters of Activity reported for each article in MEL.
Authors' eigenvector	The log transformed sum of eigenvector centralities of all co-authors of a published article. Eigenvector centrality measures the importance of an author in the co-authorship network based an author's links to collaborators, and also the collaborators' links, and their collaborators' links, etc.
Authors' betweenness	The log transformed sum of betweenness centralities of all co-authors of a published article. Betweenness centrality measures whether an author tends to be a bridge between parts of the collaboration network that would otherwise be more separated.
Authors' PageRank	The sum of PageRank centralities of all co-authors of a published article. Like eigenvector centrality, PageRank measures the importance of an author in the co-authorship network, based on links to collaborators, the collaborators' links, and their collaborators' links, etc.
Authors' degree	The log transformed sum of node degrees of all co-authors of a published article. Node degree is the number of links to an author in the co-authorship network.

Attention Scores) ~ year of publication + area diversity + focus country diversity + commodity diversity + activity diversity + geographic team diversity + local collaboration + helicopter index + gender index. To minimize multicollinearity, model 2 and 3 excluded geographic team diversity but included institutional diversity and team size, respectively. We stepwise-selected multiple regression models resulting in lower Akaike Information Criterion (AIC) values, using forward, backward, and bidirectional searches across the nine explanatory variables. We assessed log(WoS citations) as the response variable in models 4, 5, and 6, using the same explanatory variables as in models 1, 2, and 3, respectively.

We also incorporated the level of centrality of authors or institutions in collaboration networks as an explanatory variable in our models. Because the author team of an article can have both highly connected and less connected researchers simultaneously, we assessed the assumption that more connected research agents (authors or institutions) are likely to influence and contribute differently to the impact of publications (Sarigöl et al., 2014). We calculated aggregated centralities of articles based on four centralities of article authors or institutions of affiliation as calculated in the networks described above (details provided in methods section 2.3.2 and 2.3.4): node degree, betweenness, eigenvector, and PageRank. Aggregated article centralities represent the sum of the centralities of authors or institutions collaborating on an article. We fitted linear regression models to evaluate the likely relationships between article centralities and WoS citations (or Altmetric scores). Because older publications have more time for citations and attention (a phenomenon known as citation inflation), we normalized the WoS citations and Altmetric score of each article by dividing it by the annual mean number of WoS citation or annual mean Altmetric score.

3. Results

3.1. A1-A2. Understanding the structure of research collaboration networks

3.1.1. Key institutions in research collaboration networks

The inter-institutional collaboration networks of GLDC and RTB programs have high connectivity. Almost all institutions have formed links that connect into a single network in both CRPs (as opposed to networks with multiple isolated components) (Table S6–7 provide details of the CRP networks). Out of all the collaborations in these networks, 11.4% in GLDC and 14.3% in RTB were attributed to collaborations with institutions considered program participants, that is, institutions participating in CRP governance (Fig. 2). Link formation was more likely between program participants (63% for GLDC and 89% for RTB) indicating a tendency toward institutional homophily (Table S8). Link persistence in GLDC was more likely between program participants and non-program participants (73%) indicating a tendency toward institutional heterophily. Yet, link persistence in RTB was better explained by institutional homophily (79%).

Examples of hub institutions (those connecting to many other institutions in the institutional network, i.e., having a high node degree) included the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), the International Center for Agricultural Research in the Dry Areas (ICARDA) and the International Center for Tropical Agriculture (CIAT) in the GLDC (Fig. 2a), and the International Potato Center (CIP), the International Institute of Tropical Agriculture (IITA), and Bioversity International in the RTB institutional network (Fig. 2b). In both CRP networks, hub institutions often also function as bridge institutions, based on their high betweenness centrality. The number of authors affiliated with an institution is another measure of likely institutional influence. Institutions with the top 3 number of authors in the GLDC network were ICRISAT, ICARDA and the Indian Council of Agricultural Research (ICAR), each with >50 affiliated authors. In the RTB network, the top 3 were IITA, CIP, and Bioversity International, each with >104 affiliated authors.

3.1.2. Geographic priorities and key players in research collaboration networks

The geographic structure of research collaboration networks differed between the two CRPs. The two networks had distinct sets of research focus countries and countries of affiliations that had the most collaborations. Examples of research focus countries for GLDC are India, Ethiopia, Kenya, Ghana, Nigeria, and Mali (Fig. 3a), and for RTB are

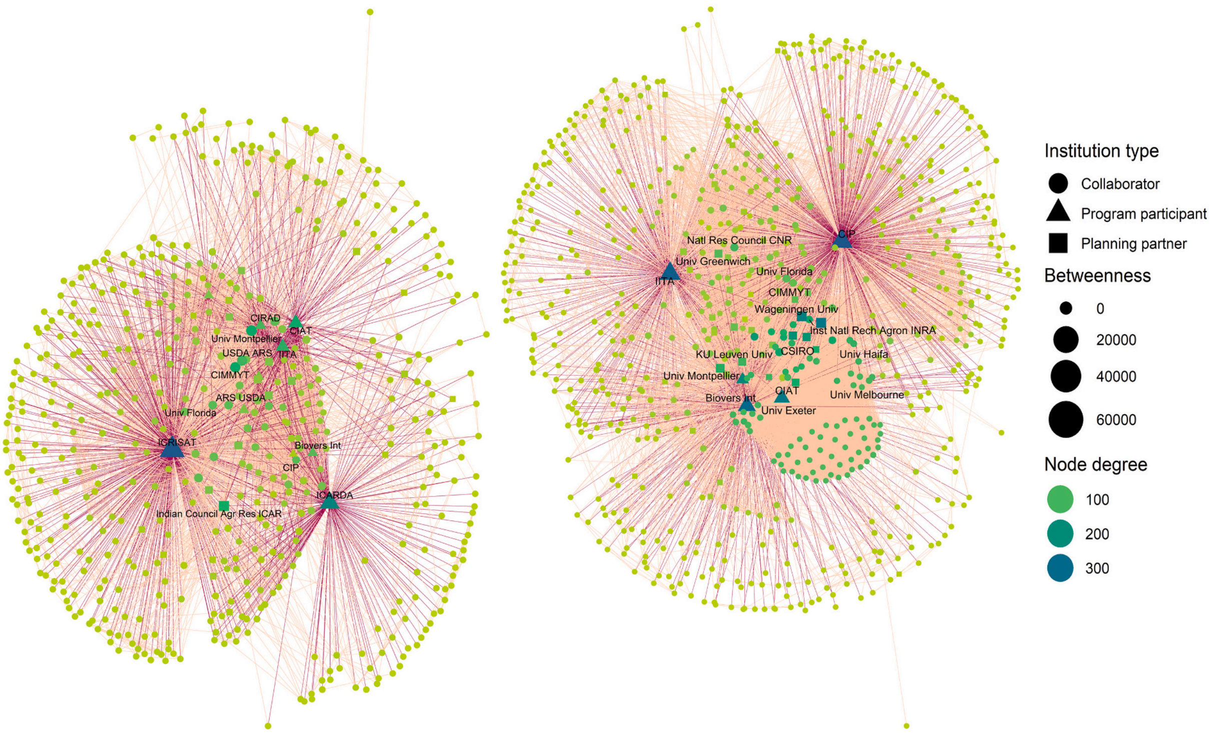


Fig. 2. Research network of institutions collaborating in two CGIAR research programs, Grain Legumes and Dryland Cereals (GLDC, left) and Roots, Tubers and Bananas (RTB, right). Individual nodes represent institutions and links represent research collaboration between institutions resulting in a journal article. Darker node color indicates higher institution node degree, larger node size indicates higher institution betweenness centrality, and the institution name is included for those with a higher institution node degree (>75). Darker pink links represent articles resulting from collaborations with CGIAR centers. Node shape represents institution categories (described in detail in *Methods*) grouped into program participants, planning partners, and institutional collaborators. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Uganda, Peru, Nigeria, Tanzania, Malawi, and Vietnam (Fig. 3b). These countries had the highest node in-strength in the country collaboration networks, which aligns with the CGIAR research strategy of considering these priority countries in each CRP. Similarly, examples of researcher affiliation countries that are particularly active in other countries (had the highest out-strength) include, in decreasing order, the United States and India for GLDC (Fig. 3a), and the United States, Tanzania, Belgium, Peru, and Nigeria for RTB (Fig. 3b).

From a regional standpoint, in the GLDC network there was high inter-regional collaboration by North America with Africa and Asia, and by Europe with Sub-Saharan Africa (Fig. 3c). In the RTB network, there was high inter-regional collaboration of Europe (and to a lesser extent North America and South America) with Sub-Saharan Africa (Fig. 3d).

Research collaboration strength between countries (link weights in the international collaboration networks) differed from geographic proximity between countries (see also sections A3-A4). For example, the United States, the country with highest out-strength in both CRP networks, was a common partner for Colombia, Peru, India, or Nigeria as indicated by link weight in the collaboration network of the RTB program (Fig. 3b and d). In the case of GLDC, the United States also conducted research with many geographically distant countries, especially with Mali and Ethiopia.

3.1.3. Gender disparity in co-authorship networks

In the co-authorship networks, we analyzed the frequency of gender collaborations in the articles published from 2017 to 2020 for RTB and 2018–2020 for GLDC (Table S8 provides details for these networks), for those authors for whom our data included known or inferred gender (Fig. 4a-b). Using Bayes theorem to determine the probability of a gender collaboration, for GLDC we found that the probability of a male collaborating with another male (male homophily) was higher than female homophily (85% versus 67%), a male collaborating with a female was 33%, and a female collaborating with a male was 37%. For RTB, male homophily was also higher than female homophily (82% versus 64%), a male collaborating with a female was 40%, and a female collaborating with a male was 39%. In both CRPs, these results indicate that (i) men are more likely to share co-authorship with another man (male homophily) than women would be, (ii) women are more likely to share co-authorship with other women (female homophily) than men would be, and (iii) gender heterophily is less likely. The TERGMs confirm these two patterns, in which gender homophily is important for explaining either link formation or persistence in co-authorship networks (Table S8). Additionally, the TERGMs indicate that homophily in the country of affiliation of authors is a strong predictor for link formation or persistence in the co-authorship networks of each CRP.

Authors with a large number of research collaborations, belonging to the top 5th percentile of co-authorships and likely acting as researcher hubs, for GLDC included Rajeev K. Varshney (with 109 collaborations), Manish K. Pandey (35), Pooran M. Gaur (26), Abhishek Rathore (24), and Shiv Kumar (22), and for RTB included Rony Swennen (145), Guy Blomme (47), Thierry Tran (44), Dominique Dufour (40), and Jan Kreuze (36).

There was an unbalanced representation of gender in publication authorship across team size, crops, Flagships, and Clusters of Activities, or WoS areas of research (Fig. S1). In general, the representation of women authors was ~29.3% ($n = 1237$) of the total scientists collaborating with either CRP. Women participated across many components of research collaboration (including crop research, Flagships, and Clusters of Activity, and research areas) (Fig. S1). Across publications in both CRPs, about 23% of the journal articles (257) included only men as authors while 76% (849) included at least one woman as author.

3.1.4. A3-A4. International collaboration to stop helicopter research

Across the geographic collaborations, 35% of GLDC and 37% of RTB

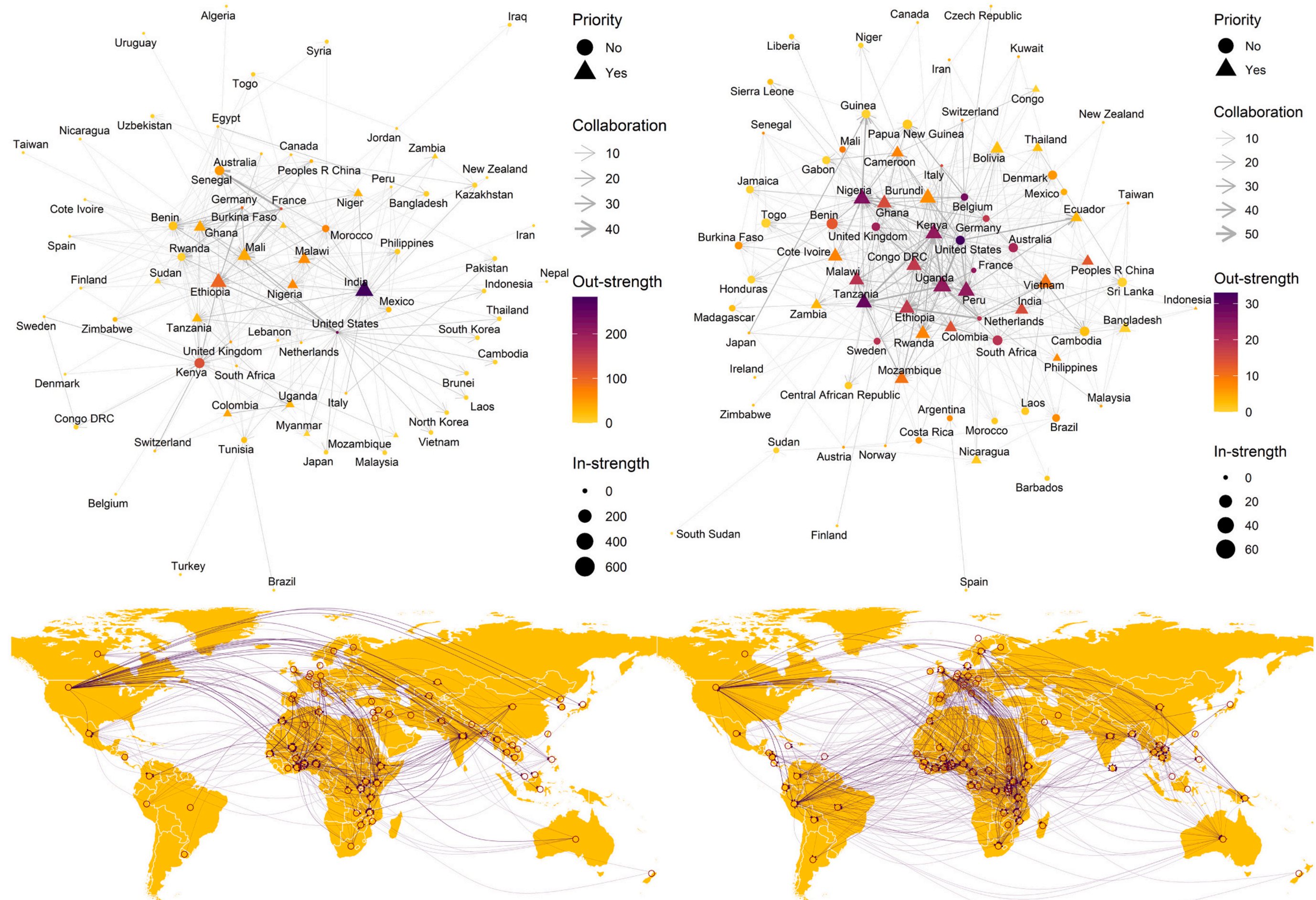


Fig. 3. Global collaboration networks for two CGIAR research programs, Grain Legumes and Dryland Cereals (GLDC, left) and Roots, Tubers and Bananas (RTB, right). Links are directed from a country of affiliation of collaborating scientists to each country where the corresponding research was conducted. Link thickness represents the total number of collaborations between these two types of countries. Publications from research by an author in their own country of affiliation can be represented as self-links, but for simplicity self-links are not shown.

country-specific collaborations corresponded to local research, that is, research was conducted in the country of an author's affiliation. Institutions and scientists that tended to conduct local research for GLDC were in India, Ethiopia, Kenya, and Malawi, with >50 articles; for RTB they were in Nigeria, Uganda, Peru, Kenya, Tanzania, and Ethiopia, with >80 articles. We also evaluated the geographic distribution of scientists and country-specific research conducted in GLDC and RTB (Fig. S2). Scientists were affiliated with 60 countries in GLDC (Table S9), with most scientists located in India (562 scientists), the United States (289), China (138), France (108), Kenya (97), Ethiopia (87), and Germany (70). Scientists were affiliated with 93 countries in RTB (Table S9), with most scientists in the United States (408), Nigeria (213), France (203), Peru (189), Kenya (166), the United Kingdom (157), China (154) and Uganda (148).

From a total of 43 countries where GLDC conducted research (Table S10), most research had no country focus (220 journal articles, or 62.15% of the total number of articles), or was conducted in India (26), Ethiopia (22), Kenya (15), Malawi (13), or Nigeria (10). From a total of 61 countries where RTB conducted research (Table S10), most research had no country focus (332 journal articles, or 50.23% of the total number of articles), or was conducted in Uganda (57), Nigeria (45), Kenya (34), Peru (33), Ethiopia (32), or Tanzania (30). When considering country-specific research, scientists and institutions were highly likely to conduct research internationally.

In both CRPs, network collaboration strength (as measured by the number of collaborations) between countries was not explained by geographic proximity. There was not a clear relationship between the number of collaborations and geographic proximity (Fig. S3), suggesting that collaboration occurred across a broad spectrum of geographic distances. Research collaboration occurred most between affiliation countries and research-focus countries in the Global South, representing 60 to 70% of all collaborations and supporting a tendency toward homophily among countries in the Global South (Table S11 provides detail for each collaboration type by CRP). Collaborations between scientists affiliated in the Global North and research-focus countries in the Global South represented 25 to 33% of all collaborations, indicating a strong tendency toward regional heterophily. Other types of collaboration in the Global South or Global North represented <10%.

3.2. The temporal dynamics of research collaboration

3.2.1. B1-B2. Evolution of research during Phase II

Each CRP showed distinct histories in agricultural research (details provided in Table 2). For example, the total number of articles published by RTB increased over four years, with a peak in 2020. The number of articles published by GLDC decreased by roughly 50% in 2019 and then comparably increased in 2020. The percentage articles indexed in the WoS Core Collection was 86% for GLDC and 93% for RTB. The percentage articles published open access was 90% for GLDC and 85% for RTB. The total number of collaborating authors fluctuated over time

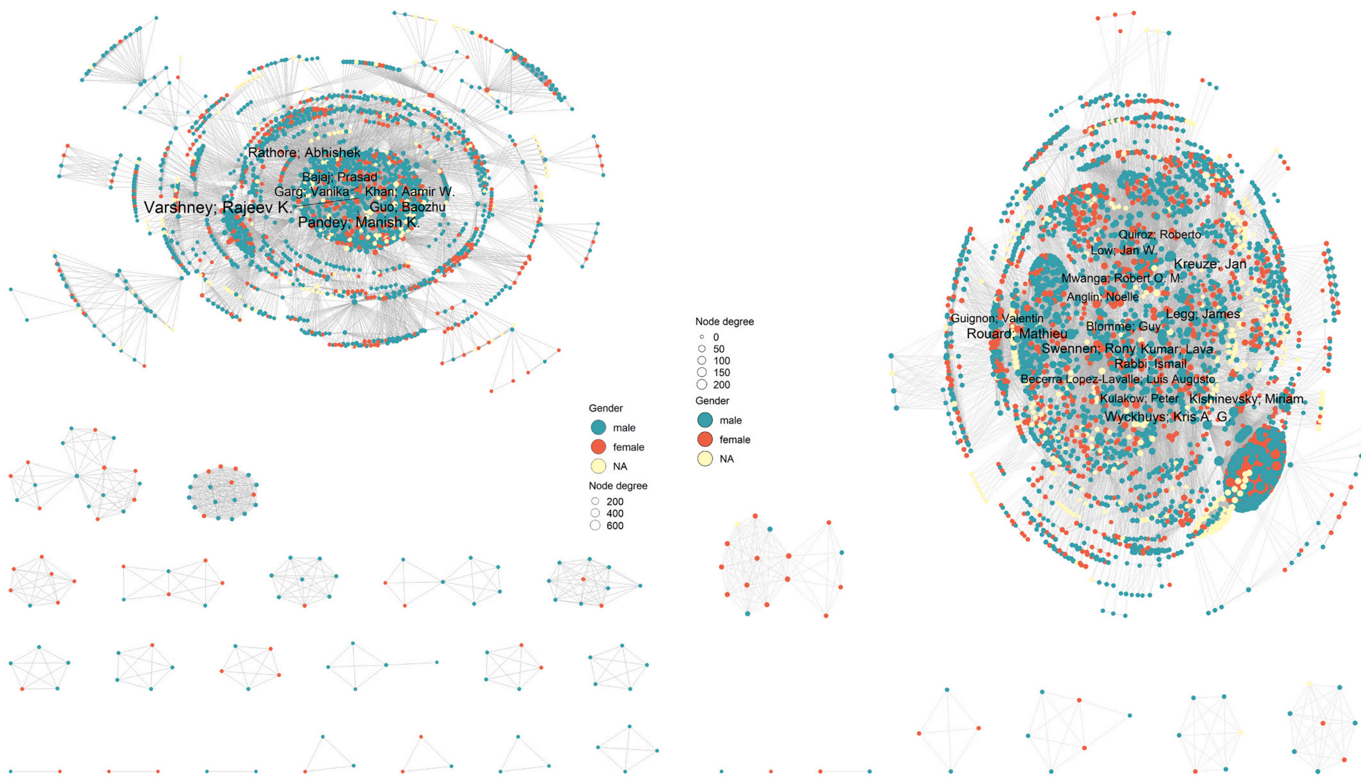


Fig. 4. Researcher co-authorship networks during Phase II for two CGIAR research programs, Grain Legumes and Dryland Cereals (GLDC, left) and Roots, Tubers and Bananas (RTB, right). Links between individual research nodes indicate co-authorship on at least one journal article. Node color indicates inferred gender of researchers for cases where inference had higher confidence. Node labels indicate the names of researchers with a node degree (number of collaborators) >150 for GLDC and 100 for RTB. The large component of these co-authorship networks includes most authors, while some authors only appear in separate small network components.

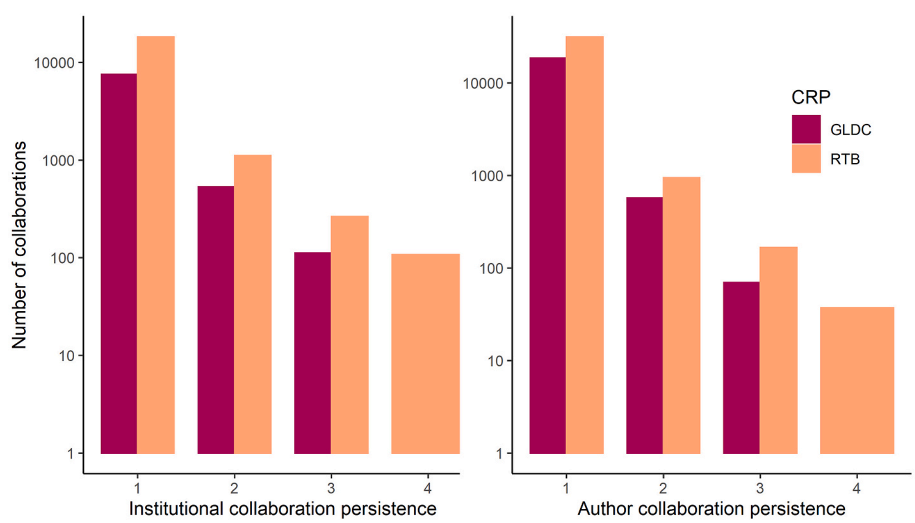


Fig. 5. Collaboration persistence in scientific publications (in years) for the CGIAR Research Programs (CRPs) on Grain Legumes and Dryland Cereals (GLDC) and Roots, Tubers and Bananas (RTB), as measured by the number of dyad collaborations between institutions (left) and authors (right) resulting in article publications, where collaboration lasted one or more consecutive years. (Note that the RTB program began a year earlier than the GLDC program, so GLDC collaborations could persist at most 3 years.)

(increasing one year and decreasing the next) for both CRPs, as did the total number of female or male authors (based on gender inferred by the Gender API).

3.2.2. B3. Declining collaboration persistence in scientific publications

Assessing articles published by both CRPs across time, we found that researchers and institutions were more likely to collaborate in a single year and less likely over multiple years (based on articles with at least two authors or institutions of affiliation; Fig. 5). The number of dyadic collaborations, based on author or institution, that resulted in publications decreased when considering longer duration collaboration (Fig. 5). Of the total dyadic collaborations, 96.7% and 96.5% of authors, and 92.1% and 84.3% of institutions, collaborated in publications for only one year in GLDC and RTB, respectively.

In the GLDC author network, 70 dyad collaborations (0.36%) between authors persisted such that they resulted in publications across the three years studied. In the RTB network, which began a year earlier, 167 dyad collaborations (0.11%) between authors persisted such that they resulted in publications across the four years studied. In the GLDC institution network, 112 dyad collaborations (1.37%) persisted between institutions with publications across the three years analyzed, and in the RTB network 108 dyad collaborations (1.98%) between institutions persisted with publications across the four years analyzed (Fig. 5). More institutional collaborations persisted over time than author collaborations.

3.3. C1. The role of CGIAR management structures in research collaboration networks

A complete summary of the short-term evolution of research collaboration networks is available in Figs. S4–6.

3.3.1. Flagship networks by CRP

Only four articles resulted from collaboration between two Flagships in GLDC; the remaining publications (98.9%) resulted from collaboration in individual Flagships. From the eight Flagships associated with GLDC, Pre-breeding and Trait Discovery (Flagship GLDC-FP5), Integrated Farm and Household Management (GLDC-FP3), and Variety and Hybrid Development (GLDC-FP4) were the Flagships supporting most articles, with 119 (33.2% of all articles from GLDC), 104 (29%), and 76 (21.2%) publications in GLDC (Fig. 6a; Table S13). Only 12 articles resulted from collaboration between two Flagships in RTB; of the remaining publications 98.1% resulted from collaboration in individual Flagships. From the five Flagships associated with RTB, Resilient RTB Crops (Flagship RTB-FP3), Adapted Productive Varieties and Quality Seed of RTB Crops (RTB-FP2), and Discovery Research for enhanced Utilization of RTB Genetic Resources (RTB-FP1) were the Flagships supporting most articles, with 180 (26.7% of all articles from RTB), 167 (24.8%), and 123 (18.3%) publications in RTB (Fig. 6b; Table S13). The evolution of collaboration between Flagships and research institutions is shown in Fig. S4.

3.4. D1. Collaboration performance

Geographic team diversity was ranked among the three most important predictor variables across the models and the article impact metrics (Fig. 7).

Based on the highest importance scores in random forest analysis, year of publication, authors' eigenvector centralities, authors' betweenness centralities, and the gender index (or the proportion of women to men) are most likely associated with the number of WoS citations of an article (Fig. 7a). Random forest importance when using Altmetric Attention Scores highlights geographic team diversity, authors' eigenvector centrality, authors' degree centrality, and authors' PageRank centrality as likely important predictors (Fig. 7b). However, local collaboration, crop diversity, geographic team diversity, and Flagship diversity were associated with the number of WoS citations based on highest Pearson correlation coefficients (Fig. 7c). Geographic team diversity, crop diversity, authors' degree centrality and authors' PageRank centrality were the most likely important predictors for Altmetric Attention Scores based on Pearson correlation coefficients (Fig. 7d). The relationships between the article Altmetric Attention Scores and WoS citations as response variables and their 13 potential explanatory variables are illustrated in Fig. S7.

Our model 1 (details in Methods, section D1) explained a large share of the variation (40.3%) in Altmetric scores for articles (details of each model in Table S14). The variance of Altmetric scores explained by models 2 and 3, where geographic team diversity was excluded but institutional diversity or team size was included, was slightly lower compared to model 1 (38.1 and 37.6%, respectively). In these three

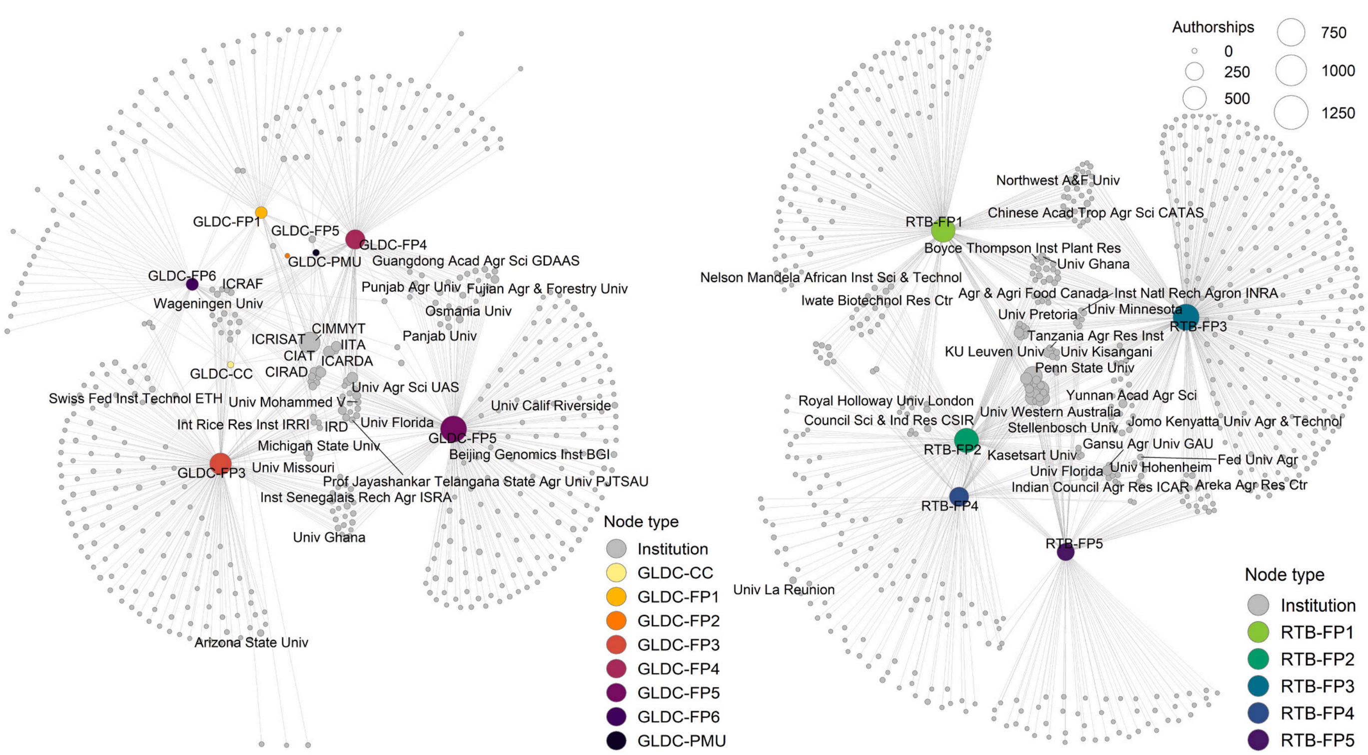


Fig. 6. Research collaboration networks for Flagships and institutions in the CGIAR Research Programs for Grain Legumes and Dryland Cereals (GLDC; left) and Roots, Tubers and Bananas (RTB; right). Grey nodes represent research institutions. Colored nodes represent Flagships in GLDC and RTB. Each link represents collaboration between scientists in Flagships and institutions that resulted in at least one journal article. Node size indicates the number of collaborations between Flagships and research organizations. Node names are displayed for institutions or Flagships connected to at least 15 nodes.

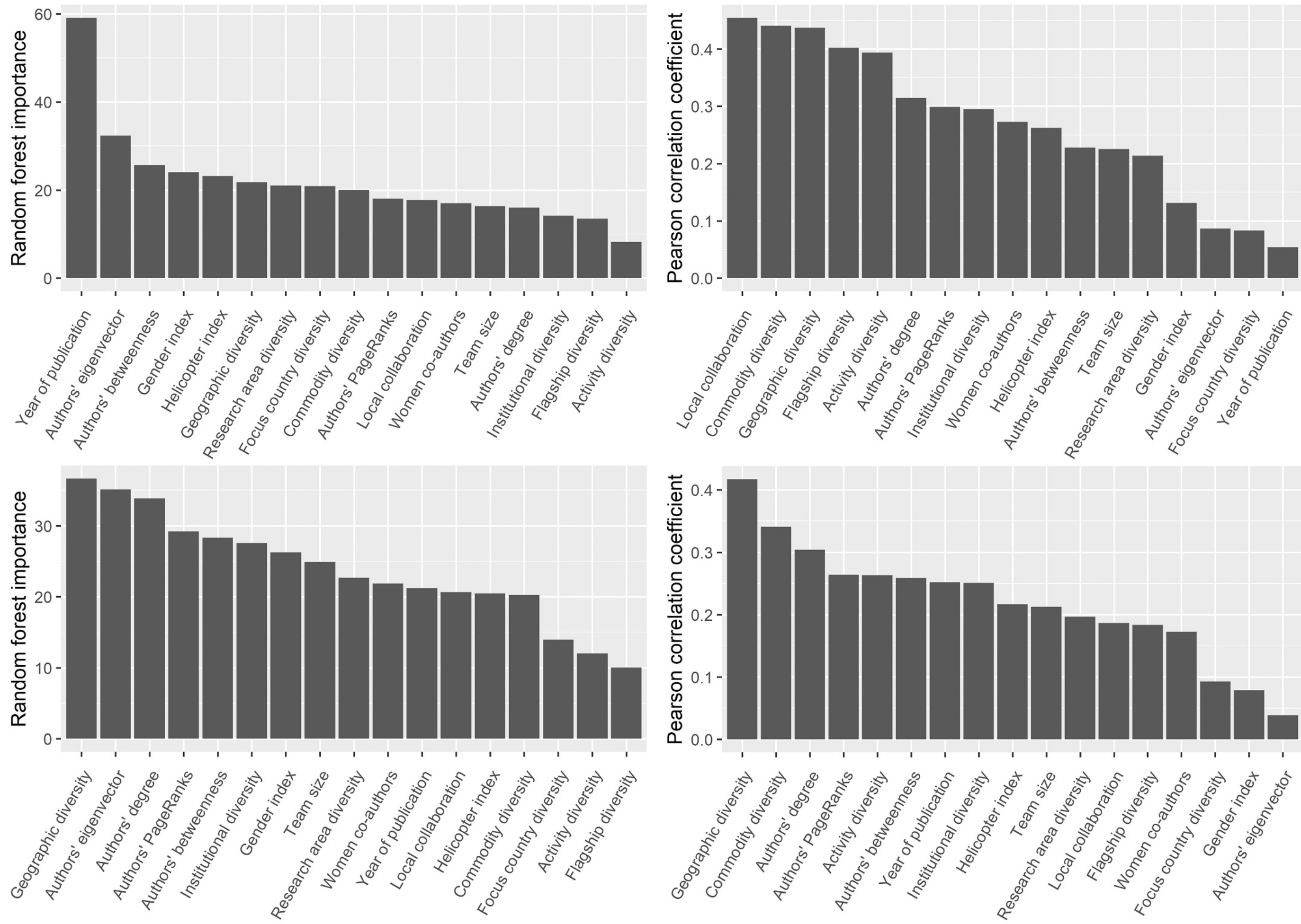


Fig. 7. Ranking factors associated with the performance of journal articles based on Web of Science (WoS) citations (top panels) and Altmetric Attention Scores (bottom panels), for articles in a single combined dataset from both the CGIAR Grain Legumes and Dryland Cereals (GLDC) and Roots, Tubers and Bananas (RTB) Research Programs. Ranking based on highest random forest importance (left panels) for log transformed WoS citations and Altmetric Attention Scores. Log transformation of WoS citations and Altmetric Scores increased Pearson correlation coefficients ($R^2 = 0.42, p < 2.2 \times 10^{-16}$; $R^2 = 0.54\ p < 2.2 \times 10^{-16}$, respectively), suggesting nonlinear relationships between citations and explanatory variables. Details of each explanatory variable are provided in Table 3 and in Methods.

models, all explanatory variables were selected regardless of the stepwise search method used and there was strong evidence for each as a predictor.

Similarly, our model 4 explained a large share of the variation (43.7%) in WoS citations for articles (Table S15). The variance of WoS citations explained by models 5 and 6, where geographic team diversity was excluded but institutional diversity or team size was included, was slightly lower compared to model 4 (43.7 and 43.5%, respectively). In the three latter models, eight explanatory variables were selected regardless of the stepwise search method used and there was strong evidence for each as a predictor. Research area diversity was not selected as a predictor in these models for WoS citations ($p = 0.263$). The summary statistics of each explanatory variable for models using Altmetric Attention scores and WoS citations are provided in Table S14–15. In the dataset including articles from both CRPs, log-transformation of WoS citations and Altmetric scores improved predictive power of our model when using the Pearson correlation coefficient, but not for random forest importance.

We also assessed the influence of article centralities, i.e., the average centralities of an article's authors on the WoS citations and Altmetric Attention Scores. The sum of authors' node degree and Page Rank were strongly associated with Altmetric Attention Scores. The sum of authors' eigenvector was also strongly associated with WoS citations and Altmetric Attention Scores. Together, these findings are consistent with two hypotheses in research for agriculture development (Fig. 1). (i) Both geographic team diversity and the centralities of authors in the co-authorship networks are consistently associated with scientific influence (WoS citations), or social influence (Altmetric Attention Scores). (ii) Multiple factors contribute differently to scientific or social influence, with some potentially playing only minor roles.

4. Discussion

We provide a network-based analytical framework for evaluating research collaboration (Table 1), applied to the CGIAR GLDC and RTB research programs. We present this as an analysis of key components of a more general conceptual framework for agricultural innovation systems to support the UN SDGs (Fig. 1). These analyses support the needs of evaluation projects, such as the CGIAR Quality of Research for Development initiative, but the new components of this framework can be used to evaluate research collaboration for any other scientific disciplines over longer time scales. Integrating multiple perspectives on collaboration, especially in scientific networks, helps to synthesize across the many missions that are pursued simultaneously in agricultural research systems for innovation and development (Klerkx and Begemann, 2020). Understanding the types of networks formed in the

CGIAR research programs helped us to quantify important aspects of scientific collaboration, such as gender parity, the scientific roles of authors and institutions in publications, patterns in "colonial science", geographic dynamics of scientific collaboration, research management dynamics, and the evolution of research (Adams, 2012; Fortunato et al., 2018; Miao et al., 2022; Olechnicka et al., 2019). These analyses provide valuable information for characterizing associations, rather than directly addressing causation. In the face of uncertainty, these observed associations can motivate further studies to understand specific mechanisms underlying the formation and improvement of collaboration in large communities of research practitioners.

4.1. Successful agricultural research systems engage more women in co-authorship networks

Co-authorship in publications is a commonly used proxy for scientific collaboration (Olechnicka et al., 2019). In both the GLDC and RTB co-authorship networks, less than a third of scientists were women, while most of the articles (76%) included at least one female author (Fig. 3a-b). A few scientists appear central. Balanced gender participation for inclusive research is a common challenge that needs to be pursued across scientific research areas in most parts of the world (Huang et al., 2020; Larivière et al., 2013). Closing the gender gap in agricultural research has the potential to better support the women who play many roles in agricultural development (Quisumbing et al., 2014), especially in cases where women scientists have a better understanding of the specific needs of women farmers. In addition to addressing issues of fairness and ethics, gender-diverse teams are likely to provide new, more integrated perspectives in (agricultural) science and technology (Ni et al., 2021), making scientific research more productive, accurate and effective (Allagnat et al., 2017), distributing co-authorship opportunities more equally in large teams (Zeng et al., 2016), and potentially improving research groups' performance through collective intelligence (Woolley et al., 2010).

Closing the gender gap could improve productivity and efficiency in agriculture (Quisumbing et al., 2014), and we found gender differences in how scientists collaborated in agricultural research. Multi-authored publications having more women (>50%) than men as authors represented only 9.5% of all publications. (This analysis excluded authors without inferred gender.) In both CRPs, women were more likely to collaborate with other women than men would be (Fig. 4). Substantially more men than women published in agricultural research conducted by both CRPs, consistent with many other fields of research (West et al., 2013). We found women were active in almost all components of agricultural research – when divided in categories such as research disciplines and Flagships – though they were comparatively under-represented in these categories. Together these findings are consistent with a Matilda effect, a scientific bias affecting women (Rossiter, 1993), although more direct study would be needed to understand what mechanisms affect levels of engagement among women.

4.2. Academically productive teams influence research collaboration networks

The position of scientists in collaboration networks indicates the potential role of key team players in leading scientific research communities in a collaborative manner (Jones et al., 2008; Li et al., 2016), where the likelihood of having such a role generally depends on a scientist's career stage (Larivière et al., 2013). Central authors are likely to have more years of experience in a research program (Guimera et al., 2005; Sarigöl et al., 2014). Our analysis identifies a set of scientists who are central in research collaboration networks of these CRPs. It is an open question what traits make a scientist successful in research collaboration, where some likely key factors such as funding rates were unavailable in this study.

A network's tendency toward homophily or heterophily – i.e., how frequently or intensely scientists collaborate with individuals having similar versus dissimilar traits – may be based on gender and other traits (Boschma, 2005; Olechnicka et al., 2019). International multidisciplinary collaboration requires research interactions between scientists with different academic or professional specializations (Li et al., 2016; Zeng et al., 2016), languages (Boschma, 2005), and career stages, such as balancing team diversity between newcomer and incumbent researchers for effective information flow through scientific networks (Wuchty et al., 2007).

4.3. Multi-institutional collaboration shapes the structure of research networks

Multi-institutional collaboration networks for both CRPs included highly connected institutions which played a leading research role as collaboration hubs (Fig. 1a-b). Few institutions played roles as bridges in the collaboration networks, suggesting weak bottleneck effects, i.e., little evidence for single institutions dictating the flow of collaborations between institutions, that could impede research linkages. Multi-institutional collaborations were distributed both within and outside CGIAR, including program participants and planning partners, which is key for crossing organizational boundaries (Boschma, 2005; Jones et al., 2008). As expected, most program participants of each CRP (who were part of the CRP governance) played a central role in the networks of these two research programs, and each had a relatively high node degree. Future studies can incorporate analysis toward understanding the collaborative roles of other common research organization types, such as universities, governmental institutes, or private crop industries (Jones et al., 2008; Ponds et al., 2007). Institutions may ignore historical relationships related to geographic proximity or colonial ties (discussed below), gaining a competitive advantage by building collaborations with institutions in high-income countries (Koseoglu, 2016).

4.4. Geographically diverse teams support agricultural research for development

The structure of international collaboration networks has the potential to influence the flow of ideas and other resources (Miao et al., 2022; Olechnicka et al., 2019). Previous analysis has characterized the structures of networks of author affiliation countries in the GLDC program (Rünzel et al., 2021), highlighting that affiliations with countries such as India, United States, Australia, Kenya and China are frequent in this CRP. Our analysis also highlights the key roles of these countries in the GLDC publications but extends into other aspects of research geography. For instance, we included in the research network analyses of both (a) countries of author affiliation and (b) countries where research has been conducted, to assess both aspects of geographic collaboration.

Since 1945, the United States and the United Kingdom have been considered research leaders across many scientific disciplines (Adams, 2012; Miao et al., 2022). Our geographic analysis is consistent with the leading role of these countries in research collaboration of both CRPs, internationally and intercontinentally (Fig. 3), underscoring these countries as important 'sources of scientists' for conducting research. Yet research-focus countries were priorities in each CRP, such as India and Ethiopia for GLDC and Uganda and Kenya for RTB, reflecting the focus on research for development which generates different network structures compared to general trends in the geography of science. Intercontinentally, GLDC focused more on Eastern and Western Africa and Southern Asia while RTB focused more on Eastern and Western Africa, South America, and Southeastern Asia. In our dataset, 46% of GLDC and RTB research was conducted in the country of at least one author affiliation in international teams, while other articles did not mention the country of focus, indicating either a shared global focus (Adams, 2012) or research without a geographic focus.

International research collaboration is crucial to equitably maximize geographic human intellectual capital (Larivière et al., 2015; Larivière et al., 2013), especially for low-income countries to be scientifically competitive (Rees et al., 2021). Nevertheless, previous studies have reported a tendency for sub-Saharan African countries to experience helicopter research from high-income countries, such as the United States, the United Kingdom, and Canada, for article publications in the medical disciplines, soil science, and ecology (Dahdouh-Guebas et al., 2003; Economou-Garcia, 2022; Minasny et al., 2020; Rees et al., 2021). This tendency for helicopter research in low-income countries likely results from limited resource availability and dependence on external support, but also shows differences due to language, funding type, and scientific journal (Adame, 2021; Rees et al., 2021). Although there is a declining trend, these prior findings highlight that 4–14% of international research resulting in publications by 2018 could be considered "helicopter science". Our dataset provides evidence for strong international collaboration between institutions headquartered in Global South countries, and between institutions in Global North countries and research-focus countries in the Global South. In our dataset, 45% of publications had a geographic research focus in Global South countries, but only 0.6% ($n = 3$) of these publications likely qualifies as helicopter science. Discussing collaborations in terms of country categorizations such as Global South and Global North can be useful, but there is a wide spectrum of economic scenarios for countries which is not captured in this dichotomy. As One CGIAR is implemented, its role in building effective collaboration networks should continue to strengthen national programs (Barrett, 2020; Byerlee and Lynam, 2020) and link with 'national innovation systems' in low- and lower-income countries (Hall et al., 2001).

Since 1980, a substantial shift toward long-distance scientific collaboration has arisen, helping break geographic barriers in many research fields, likely improving access to geographically distant research collaborators, and suggesting a modern geographic expansion in knowledge transfer (Adams, 2012; Jones et al., 2008; Waltman et al., 2011). Our results are consistent with previous studies suggesting that geographic proximity plays a minor role in research collaboration at large scales (Ponds et al., 2007). We found that agricultural research collaboration often occurs across regional and international scales, highlighting how scientists and institutions collaborate over long distances (i.e., hundreds or thousands of kilometers). However, this geography of research collaboration can depend on the regional specialization of scientific fields (Miao et al., 2022), as our analysis indicates for the specific research roles of countries in each CRP. Individual countries and their governments have a range of different priorities and levels of investment. Geographic proximity may be relevant for structuring research collaboration within countries (Olechnicka et al., 2019), such as when collaboration is based on face-to-face interactions (Ponds et al., 2007). Finer spatial resolution for research locations and for author affiliations will be important in future analysis. Future studies may also focus on the effects of scientist mobility or migration, as these may be important factors for research collaboration in some disciplines (Sugimoto et al., 2017). Scientific teams with cognitive (such as language), social, political, cultural and technological differences can have both additional transaction costs and additional benefits (Adams, 2012; Olechnicka et al., 2019).

4.5. Multidisciplinary teams are needed to address complex agricultural challenges

The unique structure of research collaboration networks generally represents the underlying preferential selection of collaborators, fostering collaboration dependent on available funding and infrastructures, established responsibilities, social preferences, and scientific needs of research agents (scientists, institutions or countries) (Fortunato et al., 2018; Olechnicka et al., 2019). The complexity of scientific challenges in agriculture also plays a crucial role in structuring research collaboration networks. In our dataset, we identified emerging complex interdisciplinary topics in agriculture – crop genomics, bioinformatics for modern genomic breeding, global landscape effects on pest communities, climate change effects on crop yield, crop diversity and crop diversity conservation – which require a large-scale, integrated scientific collaboration of institutionally and geographically diverse teams for conducting research and publishing articles.

Studies commonly emphasized the focus crop species for each CRP in addition to other crops (Box S2), showing the breadth of research and highlighting, for example, the importance of intercropping system (e.g., potatoes and legumes for RTB) and research in alternative production systems. The One CGIAR transition (CGIAR System Organization, 2021), which was implemented when the CRPs ended, moved away from focus crops with the aim to integrate and synergize across disciplines and cropping systems. New programs include studies which address multiple crops or intercropping systems in order to address a wider audience and integrate food systems.

4.6. Long-lasting teams collectively assemble the core structure of research collaboration networks

Scientific collaboration is an evolving social process: after initiation, a collaboration can cease or continue steadily or intermittently, strengthen or weaken, and new collaborations can form or re-emerge (Guimera et al., 2005; Olechnicka et al., 2019). In this study, our proxy for scientific collaboration persistence is the number of years two authors (or institutions) published together (Olechnicka et al., 2019). Most of the author and institutional collaborations did not persist in terms of co-authorship across multiple years, though the collaborations between institutions were more persistent than author collaborations. Most scientists and institutions had 'ephemeral' collaborations, positioned in the periphery of collaboration networks, and only a few repeatedly collaborated over time, being central in the collaboration networks. These results are consistent with findings about research collaboration ties in other fields of science outside agriculture (Dahlander and McFarland, 2013; Wang and Barabasi, 2021). Because research agents age, retire, change careers, or shift funding sources, scientific collaboration networks often have a high turnover rate, with most ties lasting only one or a few years (Guimera et al., 2005; Petersen, 2015). However, a challenge to studying the persistence of collaboration (in terms of years of publication) is that ambitious projects resulting in a single publication may need several years of research collaboration for completion. The publication of scientific articles often experiences a delay, so relying on the number of article publications does not necessarily show the actual scientific progress and ultimate productivity by CRPs within a year. We studied these CRP networks during a relatively short time window, supporting early assessment, but representing only a snapshot of the past decades of research evolution. Early assessments can help in evaluating the current state of research while planning immediate responses to research needs (Immonen and Cooksy, 2019). Some aspects, such as the number of citations (discussed below), continue to change over time, and long-term evaluations can consider this time lag in final research products as data become available. With One CGIAR's new focus on cross-disciplinary integration, a key task is learning how to strengthen, maintain, and form new scientific ties moving into future high impact research. In practice, a key question is what time period new initiatives can consider to be an effective lifespan for future research program evaluations.

Collaboration is increasingly widespread in the scientific community, cutting across substantial cultural differences and geographical distance among countries, and online communication networks have fostered research collaboration (Ponds et al., 2007). Future analyses of collaboration networks could focus on additional aspects of research success as data become available (Table S1). For instance, the structure of collaboration networks is influenced by the strength of contributions in scientific article production: inclusion of credit allocation is becoming more common and can be considered in future analysis of research networks (Olechnicka et al., 2019). Other types of collaboration in science that can more fully represent the structure of research collaboration include collaborations for modeling, as in platforms for collaborative programming such as GitHub, and those indicated in article acknowledgements. We focused on dyadic or pair-wise collaborations between authors or institutions, while triadic (simultaneous collaboration among three authors or institutions) and high-order team structures, could potentially be evaluated in hypergraphs (Battiston et al., 2020). Another aspect for future evaluation is the availability of funding to research groups as a key driver of research productivity.

4.7. Project traits associated with research success in agricultural systems

Scientometrics applications across fields of science indicate that citation success is driven by multiple factors, often including different aspects of publications (e.g., quality, topic, open accessibility, novelty), journals (e.g., impact factor), and authors (e.g., self-citations, co-authorship, h-index) (Leimu and Koricheva, 2005; Tahamtan et al., 2016; Vanclay, 2013). In agricultural research, quantitative understanding of which factors affect the multi-faceted, complex dynamics of citation rates of publications is limited. Our new study generates the data-driven hypothesis that articles with more citations are positively associated with greater geographic diversity of authors and, though less consistently, publication year, participation of local scientists, and women co-authors. Altmetric Attention Scores offer an alternative to citation rates, highlighting communication about publications in social media and online platforms of research communities, through which research results potentially gain rapid attention, and potentially reach portions of the public less likely to directly access scientific papers (Akella et al., 2021; Olechnicka et al., 2019; Thelwall et al., 2013). Our analysis indicates that 'social influence' based on Altmetric Attention Scores is also associated with geographically diverse co-author teams and, less strongly, institutional diversity and crop diversity, consistent with previous findings about the key role of geographic team diversity in future citation success (Olechnicka et al., 2019; Thelwall and Nevill, 2018). More interestingly, we find a strong positive association between the average connectivity of scientists (or institutions) in research collaboration networks and citation rates (or Altmetric Attention Scores), which is consistent across different network metrics (Fig. 7). These findings suggest that teams of scientists (and institutions) may drive scientific and social influences through their key roles in research network structures, potentially influencing greater visibility and preferential attention for publications from "highly collaborative authors or institutions". Our results support this 'scientific or social influence' hypothesis, as previously articulated in co-authorship network analyses from the field of computer science (Sarigöl et al., 2014).

Because scientific articles can accumulate citations over many years or even decades (Fortunato et al., 2018; Thelwall and Nevill, 2018), our results here based on citations show only the early impacts of publications in current agricultural research communities. A fuller view of publication success could incorporate other aspects, such as rejection rates, time and funding required to achieve experimental outcomes that resulted in a publication, and unpublished outcomes. There is a tendency for higher citation rates in some scientific disciplines compared to others (Fortunato et al., 2018; Vanclay, 2013). When disciplines can be clearly defined, the success of research papers could be standardized based on typical citation rates in a paper's discipline.

The number of citations highlights just one dimension of research success (Fig. 1), representing a quantitative proxy of adoption of ideas among scientists (Hall et al., 2001) but stopping short of analysis of technology adoption by growers. Studying research networks is crucial to understanding how administrative decisions for developing research programs are translated into successful and impactful research. In agricultural research for development, the success of research projects depends on multiple aspects emphasized by stakeholders (Olechnicka et al., 2019), such as funders' societal goals, scientists' interests, and farmers' needs. The final measure of agriculture research success can thus incorporate components such as the dissemination of knowledge, theoretical discoveries, technology transfer, policy design, deployment of new crop varieties, yield improvement, poverty reduction, economic prosperity, and human wellbeing (Fig. 1).

4.8. The broader context for future agricultural innovations to achieve SDGs

In the analytical framework we present here, we focus on the collaboration network traits and the outcomes of research that are available for all of the published research in the GLDC and RTB: WoS citations and Altmetric Attention Scores. Researcher collaboration networks are linked to farmers in ways that would require different research approaches to study; and once the information and technologies from research are known to growers, the specific links among growers influence who has ready access to technologies (Aguilar-Gallegos et al., 2015). Evaluating linked social and biological networks, across relevant stakeholders, can reveal how adoption of management influences biological networks, such as the spread of new varieties or the spread of crop pathogens (Bodin et al., 2017; Etherton et al., 2023; Garrett, 2021). Impact pathway analysis specifies how research is intended to provide benefits, so that whether and how these benefits are being realized can be continually evaluated (Springer-Heinze et al., 2003). The theory of change for how researcher engagement can improve outcomes includes the potential to produce better links to the market, build social capital, change institutions, and build innovation capacity (Maru et al., 2018).

The effects of research networks may vary depending on the types of agricultural technologies being developed. It has often been difficult to realize adoption of management practices and improvements to natural resource management at scale - compared to genetic improvements and adoption of new varieties – although new management practices may provide at least as great a benefit (Stevenson et al., 2019) (Byerlee and Lynam, 2020). Collaboration networks take on new importance in digital agriculture and transitions to smart farming technologies, and the type of network required for successful adoption may vary from applications such as use of agricultural apps to use of methods that depend on in-field GPS (Kernecker et al., 2021). In practice, disruptive technologies may generate trade-offs, providing benefits in terms of some of the SDGs but detriments in terms of other goals, so broader system consideration is necessary (Herrero et al., 2021).

In the long run, it will be helpful for analyses to provide more direct advice for decision-makers administering groups such as CGIAR. Impact assessment can range from academic research to use-focused evaluation for decision-makers (Mackay and Horton, 2003). Impact pathway analysis specifies how research is intended to provide benefits, so that whether and how these benefits are being realized can be continually evaluated (Springer-Heinze et al., 2003). Research portfolios will generally need to range from projects addressing fundamental questions, to translational research, and to adaptive research that provides high 'value of information' for local decision making (Buddenhagen et al., 2022). Ultimately, as research networks and their impacts on societal goals are better understood, it may be possible to identify tipping points and nonlinear effects, such as a critical mass of researchers in a particular discipline or a critical mass of stakeholders engaged with researchers (Garrett, 2021; Vespignani, 2009).

A fuller view of all the components of our conceptual diagram (Fig. 1) will be needed to provide definitive advice supporting administrative decisions about research program strategy, structure, and operations. Meinke et al. (2023) discuss three perspectives on improving the benefits from research. The first is use of a Quality of Research for Development (QoR4D) framework, considering research relevance, scientific credibility, legitimacy, and effectiveness (i.e., whether results are "positioned for use"). The second is use of a comparative advantage analysis, considering advantage in terms of incentives, human capital, biophysical capital, and social capital. The third is inclusive innovation based on effective engagement with stakeholders. Important progress may be made in translating and adapting results based on our analytical framework as researchers continually develop better ways to formulate project management questions and better ways to customize analyses to answer those questions. Randomized control trials (RCTs) are an interesting possibility, in which different types of project management strategies, structures, and operations would be implemented in replicate research networks. RCTs would be the ultimate approach to understanding causal relationships between research administration decisions and system impacts, but they would be challenging to implement in times of limited research budgets. For now, this analysis of GLDC and RTB provides a baseline and framework for future analyses.

CRediT authorship contribution statement

Aaron I. Plex Sulá: Conceptualization, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Valentina De Col:** Conceptualization, Data curation, Investigation, Methodology, Resources, Validation, Writing – original draft, Writing – review & editing. **Berea A. Etherton:** Conceptualization, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Yanru Xing:** Conceptualization, Formal analysis, Methodology, Visualization. **Amogh Agarwal:** Formal analysis, Investigation, Methodology, Software, Writing – original draft. **Lejla Ramić:** Formal analysis, Investigation, Methodology, Software, Writing – original draft. **Enrico Bonaiuti:** Conceptualization, Data curation, Resources, Supervision, Writing – original draft, Writing – review & editing. **Michael Friedmann:** Conceptualization, Data curation, Investigation, Resources, Writing – original draft. **Claudio Proietti:** Conceptualization, Data curation, Investigation, Resources, Writing – original draft. **Graham Thiele:** Conceptualization, Funding acquisition, Investigation, Writing – original draft, Writing – review & editing. **Karen A. Garrett:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

G. Thiele was Director, E. Bonaiuti was the Program Management Officer (2021), C. Proietti was the Program Management officer (before 2021) and M. Friedmann was the Science Officer, of the CGIAR Research Program on Roots, Tubers and Bananas (RTB) led by the International Potato Center (CIP).

E. Bonaiuti was MEL Lead (2020−2021) and V. De Col was Social Network Analysis Research Fellow (2021) of the CGIAR Research Program on Grain Legumes and Dryland Cereals.

K. A. Garrett, A. I. Plex Sulá, and Y. Xing have received research funding from the CGIAR Research Program on Roots, Tubers and Bananas (RTB) and the CGIAR Research Program on Grain Legumes and Dryland Cereals (GLDC).

Data availability

The dataset used in this study is publicly available at https://hdl.handle.net/20.500.11766.1/FK2/NHJDNA. The R code for the analyses is available at https://github.com/GarrettLab/CGIAR_research_networks.

Acknowledgements

This research was initiated as part of the CGIAR Research Programs on Grain Legumes and Dryland Cereals (GLDC) and Roots, Tubers and Bananas (RTB) and supported by CGIAR Trust Fund contributors https://www.cgiar.org/funders/. We also appreciate support by the International Potato Center (CIP). The authors thank Dr. R. A. Mouafo Tchinda and Dr. N. Kraisitudomsook for helpful discussions and Agricultural Systems reviews for inspiring improvements in the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2024.104013.

References

Adame, F., 2021. Meaningful collaborations can end 'helicopter research'. Nature 34188244.
Adams, J., 2012. The rise of research networks. Nature 490, 335–336.
Aguilar-Gallegos, N., Muñoz-Rodríguez, M., Santoyo-Cortés, H., Aguilar-Ávila, J., Klerkx, L., 2015. Information networks that generate economic value: a study on clusters of adopters of new or improved technologies and practices among oil palm growers in Mexico. Agric. Syst. 135, 122–132.
Akella, A.P., Alhoori, H., Kondamudi, P.R., Freeman, C., Zhou, H., 2021. Early indicators of scientific impact: predicting citations with altmetrics. J. Inf. Secur. 15, 101128.
Allagnat, L., Berghmans, S., Falk-Krzesinski, H.J., Hanafi, S., Herbert, R., Huggett, S., Tobin, S., 2017. Gender in the global research landscape, pp. 1–96.
Barrett, C.B., 2020. On research strategy for the new one CGIAR: Editor's introduction. Food Policy 91, 101844.
Battiston, F., Cencetti, G., Iacopini, I., Latora, V., Lucas, M., Patania, A., Young, J.-G., Petri, G., 2020. Networks beyond pairwise interactions: structure and dynamics. Phys. Rep. 874, 1–92.
Bettencourt, L.M.A., Kaiser, D.I., Kaur, J., 2009. Scientific discovery and topological transitions in collaboration networks. J. Inf. Secur. 3, 210–221.
Bischl, B., Lang, M., Kotthoff, L., Schiffner, J., Richter, J., Studerus, E., Casalicchio, G., Jones, Z., 2016. mlr: Machine learning in R. J. Mach. Learn. R 17, 1–5.
Bodin, Ö., Sandström, A., Crona, B., 2017. Collaborative networks for effective ecosystem-based management: a set of working hypotheses. Policy Stud. J. 45, 289–314.
Bonechi, F., Bonaiuti, E., Graziano, V., Poole, E.J., 2019. General Dataset Curation Guide (GDCG): Part I: Curation of Datasets to Facilitate their Use and Re-Use (with Microsoft Excel).
Boschma, R.A., 2005. Proximity and innovation: a critical assessment. Reg. Stud. 39, 61–74.
Broad, W.J., 1981. The publishing game - getting more for less. Science 211, 1137–1139.
Buddenhagen, C.E., Xing, Y., Andrade Piedra, J., Forbes, G.A., Kromann, P., Navarrete, I., Thomas-Sharma, S., Choudhury, R.A., Andersen, K.F., Schulte-Geldermann, E., Etherton, B.A., Plex Sulá, A.I., Garrett, K.A., 2022. Where to invest project efforts for greater benefit: a framework for management performance mapping with examples for potato seed health. Phytopathology 112, 1431–1443.
Byerlee, D., Dubin, H.J., 2009. Crop improvement in the CGIAR as a global success story of open access and international collaboration. Int. J. Commons 4, 452–480.
Byerlee, D., Lynam, J.K., 2020. The development of the international center model for agricultural research: a prehistory of the CGIAR. World Dev. 135, 105080.
CGIAR System Organization, 2021. CGIAR 2030 Research and Innovation Strategy: Transforming Food, Landm and Water Systems in a Climate Crisis, Montpellier, France, pp. 1–36.
Csárdi, G., Nepusz, T., 2006. The igraph software package for complex network research. InterJ. Complex Syst. 1695.
Dahdouh-Guebas, F., Ahimbisibwe, J., van Moll, R., Koedam, N., 2003. Neo-colonial science by the most industrialised upon the least developed countries in peer-reviewed publishing. Scientometrics 56, 329–343.
Dahlander, L., McFarland, D.A., 2013. Ties that last: tie formation and persistence in research collaborations over time. Adm. Sci. Q. 58, 69–110.
Economou-Garcia, A., 2022. The north 'helicoptering' into the south: a meta-analysis of parachute science in ecological field studies. Student Publications 1020, 1–47.
Etherton, B.A., Choudhury, R.A., Alcalá-Briseño, R.I., Xing, Y., Plex Sulá, A.I., Carrillo, D., Wasielewski, J., Stelinski, L., Grogan, K.A., Ballen, F., Blare, T., Crane, J., Garrett, K.A., 2023. Are avocados toast? A framework to analyze decision-making for emerging epidemics, applied to laurel wilt. Agric. Syst. 206, 103615.
Fortunato, S., Bergstrom, C.T., Borner, K., Evans, J.A., Helbing, D., Milojevic, S., Petersen, A.M., Radicchi, F., Sinatra, R., Uzzi, B., Vespignani, A., Waltman, L., Wang, D., Barabasi, A.-L.S., 2018. Science of science. Science 359, eaao0185.
Garrett, K.A., 2021. Impact network analysis and the INA R package: decision support for regional management interventions. Methods Ecol. Evol. 12, 1634–1647.
Garrett, K.A., Andersen, K.F., Asche, F., Bowden, R.L., Forbes, G.A., Kulakow, P.A., Zhou, B., 2017. Resistance genes in global crop breeding networks. Phytopathology 107, 1268–1278.
Guimera, R., Uzzi, B., Spiro, J., Nunes Amaral, L.A., 2005. Team assembly mechanisms determine collaboration network structure and team performance. Science 308, 697–702.
Hall, A., Bockett, G., Taylor, S., Sivamohan, M., Clark, N., 2001. Why research partnerships really matter: innovation theory, institutional arrangements and implications for developing new technology for the poor. World Dev. 29, 783–797.
Herrero, M., Thornton, P.K., Mason-D'Croz, D., Palmer, J., Bodirsky, B.L., Pradhan, P., Barrett, C.B., Benton, T.G., Hall, A., Pikaar, I., 2021. Articulating the effect of food systems innovation on the sustainable development goals. Lancet Planet. Health 5, e50–e62.

Huang, J., Gates, A.J., Sinatra, R., Barabasi, A.-L.S., 2020. Historical comparison of gender inequality in scientific careers across countries and disciplines. Proceedings of the National Academy of Science of the United States of America 117, 4609–4616.
Immonen, S., Cooksy, L., 2019. Role and use of independent evaluation in development-oriented agricultural research: the case of CGIAR, an agricultural research network. Outlook on Agriculture 48, 94–104.
Jones, B.F., Wuchty, S., Uzzi, B., 2008. Multi-university research teams: shifting impact, geography, and stratification in science. Science 322, 1259–1262.
Katz, J.S., Martin, B.R., 1997. What is research collaboration? Res. Policy 26, 1–18.
Kernecker, M., Busse, M., Knierim, A., 2021. Exploring actors, their constellations, and roles in digital agricultural innovations. Agric. Syst. 186, 102952.
Klerkx, L., Begemann, S., 2020. Supporting food systems transformation: the what, why, who, where and how of mission-oriented agricultural innovation systems. Agric. Syst. 184, 102901.
Koseoglu, M.A., 2016. Mapping the institutional collaboration network of strategic management research: 1980–2014. Scientometrics 109, 203–226.
Krivitsky, P., Handcock, M., 2023. tergm: Fit, simulate and diagnose models for network evolution based on exponential-family random graph models. The Statnet Project. https://statnet.org.
Larivière, V., Ni, C., Gingras, Y., Cronin, B., Sugimoto, C.R., 2013. Bibliometrics: global gender disparities in science. Nature 504, 211–213.
Larivière, V., Gingras, Y., Sugimoto, C.R., Tsou, A., 2015. Team size matters: collaboration and scientific impact since 1900. J. Assoc. Inf. Sci. Technol. 66, 1323–1332.
Leimu, R., Koricheva, J., 2005. What determines the citation frequency of ecological papers? Trends Ecol. Evol. 20, 28–32.
Li, L., Catala-Lopez, F., Alonso-Arroyo, A., Tian, J., Aleixandre-Benavent, R., Pieper, D., Ge, L., Yao, L., Wang, Q., Yang, K., 2016. The global research collaboration of network meta-analysis: a social network analysis. PLoS One 11, e0163239.
Lin Pedersen, T., 2021. ggraph: An implementation of grammar of graphics for graphs and networks. R package version 2.0.5. 143.
Mackay, R., Horton, D., 2003. Expanding the use of impact assessment and evaluation in agricultural research and development. Agric. Syst. 78, 143–165.
Maru, Y., Sparrow, A., Stirzaker, R., Davies, J., 2018. Integrated agricultural research for development (IAR4D) from a theory of change perspective. Agric. Syst. 165, 310–320.
McEwan, M., Almekinders, C., Andrade-Piedra, J., Delaquis, E., Garrett, K., Kumar, L., Mayanja, S., Omondi, B., Rajendran, S., Thiele, G., 2021. "Breaking through the 40% adoption ceiling: Mind the seed system gaps." A perspective on seed systems research for development in One CGIAR. Outlook on Agriculture 50, 5–12.
Meinke, H., Ash, A., Barrett, C.B., Smith, A.G., Graff Zivin, J.S., Abera, F., Garcia, M., Just, D.R., Obokoh, N.H., Kadiyala, S., 2023. Evolution of the One CGIAR's research and innovation portfolio to 2030: approaches, tools, and insights after the reform. npj Sustain. Agric. 1, 6.
Miao, L., Murray, D., Jung, W.S., Lariviere, V., Sugimoto, C.R., Ahn, Y.Y., 2022. The latent structure of global scientific development. Nat. Hum. Behav. 6, 1206–1217.
Milojevic, S., 2014. Principles of scientific research team formation and evolution. Proc. Natl. Acad. Sci. U. S. A. 111, 3984–3989.
Minasny, B., Fiantis, D., Mulyanto, B., Sulaeman, Y., Widyatmanti, W., 2020. Global soil science research collaboration in the 21st century: time to end helicopter research. Geoderma 373, 114299.
National Research Council, N., 2015. In: Cooke, N.J., Hilton, M.L. (Eds.), Enhancing the Effectiveness of Team Science. The National Academies Press, Washington (DC), p. 281.
Ni, C., Smith, E., Yuan, H., Lariviere, V., Sugimoto, C.R., 2021. The gendered nature of authorship. Sci. Adv. 7, eabe4639.
Olechnicka, A., Ploszaj, A., Celińska-Janowicz, D., 2019. The Geography of Scientific Collaboration. Routledge Taylor & Francis Group, United Kingdom.
Petersen, A.M., 2015. Quantifying the impact of weak, strong, and super ties in scientific careers. Proceedings of the National Academy of Science of the United States of America 112, E4671–E4680.
Ponds, R., van Oort, F., Frenken, K., 2007. The geographical and institutional proximity of research collaboration. Pap. Reg. Sci. 86, 423–443.
Quisumbing, A.R., Meinzen-Dick, R., Raney, T.L., Croppenstedt, A., Behrman, J.A., Peterman, A., 2014. Gender in Agriculture: Closing the Knowledge Gap. Springer, FAO, and IFPRI.
R Core Team, 2022. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing.
Reardon, T., Echeverria, R., Berdegué, J., Minten, B., Liverpool-Tasie, S., Tschirley, D., Zilberman, D., 2019. Rapid transformation of food systems in developing regions: highlighting the role of agricultural research & innovations. Agric. Syst. 172, 47–59.
Rees, C.A., Ali, M., Kisenge, R., Ideh, R.C., Sirna, S.J., Britto, C.D., Kazembe, P.N., Niescierenko, M., Duggan, C.P., Manji, K.P., 2021. Where there is no local author: a network bibliometric analysis of authorship parasitism among research conducted in sub-Saharan Africa. BMJ Glob. Health 6, e006982.
Rhys, H.I., 2020. Linear regression. In: Michaels, M. (Ed.), Machine Learning with R, the tidyverse, and mlr. Manning Publications Co., p. 538
Rossiter, M.W., 1993. The Matthew Matilda effect in science. Soc. Stud. Sci. 23, 325–341.
Rünzel, M., Sarfatti, P., Negroustoueva, S., 2021. Evaluating quality of science in CGIAR research programs: use of bibliometrics. Outlook on Agriculture 50, 130–140.
Santamaría, L., Mihaljević, H., 2018. Comparison and benchmark of name-to-gender inference services. Peer J Computer Sci. 4, e156.
Sarigöl, E., Pfitzner, R., Scholtes, I., Garas, A., Schweitzer, F., 2014. Predicting scientific success based on coauthorship networks. EPJ Data Sci. 3, 9.
Springer-Heinze, A., Hartwich, F., Henderson, J.S., Horton, D., Minde, I., 2003. Impact pathway analysis: an approach to strengthening the impact orientation of agricultural research. Agric. Syst. 78, 267–285.
Stevenson, J., Vanlauwe, B., Macours, K., Johnson, N., Krishnan, L., Place, F., Spielman, D., Hughes, K., Vlek, P., 2019. Farmer adoption of plot-and farm-level natural resource management practices: between rhetoric and reality. Glob. Food Sec. 20, 101–104.
Sugimoto, C.R., Robinson-Garcia, N., Murray, D.S., Yegros-Yegros, A., Costas, R., Larivière, V., 2017. Scientists have most impact when they're free to move. Nature 550, 29–31.
Tahamtan, I., Safipour Afshar, A., Ahamdzadeh, K., 2016. Factors affecting number of citations: a comprehensive review of the literature. Scientometrics 107, 1195–1225.
Thelwall, M., Nevill, T., 2018. Could scientists use Altmetric.com scores to predict longer term citation counts? J. Inf. Secur. 12, 237–248.
Thelwall, M., Haustein, S., Lariviere, V., Sugimoto, C.R., 2013. Do altmetrics work? Twitter and ten other social web services. PLoS One 8, e64841.
Vanclay, J.K., 2013. Factors affecting citation rates in environmental science. J. Inf. Secur. 7, 265–271.
Vespignani, A., 2009. Predicting the behavior of techno-social systems. Science 325, 425–428.
Waltman, L., Tijssen, R.J.W., Eck, N.J.V., 2011. Globalisation of science in kilometres. J. Inf. Secur. 5, 574–582.
Wang, D., Barabasi, A.-L., 2021. The Science of Science: The Science of Collaboration. Cambridge University Press.
West, J.D., Jacquet, J., King, M.M., Correll, S.J., Bergstrom, C.T., 2013. The role of gender in scholarly authorship. PLoS One 8, e66212.
Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis. Springer, Verlag New York.
Woolley, A.W., Chabris, C.F., Pentland, A., Hashmi, N., Malone, T.W., 2010. Evidence for a collective intelligence factor in the performance of human groups. Science 330, 686–688.
Wu, L., Wang, D., Evans, J.A., 2019. Large teams develop and small teams disrupt science and technology. Nature 566, 378–382.
Wuchty, S., Jones, B.F., Uzzi, B., 2007. The increasing dominance of teams in production of knowledge. Science 316, 1036–1039.
Zeng, X.H., Duch, J., Sales-Pardo, M., Moreira, J.A., Radicchi, F., Ribeiro, H.V., Woodruff, T.K., Nunes Amaral, L.A., 2016. Differences in collaboration patterns across discipline, career stage, and gender. PLoS Biol. 14, e1002573.