Open Science, Open Sharing, and Open Data: An Analysis of Their Relationships (Postprint)

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Abstract

[Purpose/Significance] By clarifying the tripartite relationship among open science, open sharing, and open data, this study provides theoretical guidance for the practice of scientific data open sharing in China. [Method/Process] Employing normative analysis, and based on sorting out and defining the definitions and characteristics of open science, open sharing, and open data, it analyzes the pairwise relationships and the overall relationship among the three. [Results/Conclusion] A trinity logical relationship exists among open science, open sharing, and open data. Open data constitutes the material foundation for both open sharing and open science, open sharing serves as the bridge between open data and open science, and open science represents the ultimate goal of open data and open sharing. Different stakeholders need to contribute their efforts to open science in order to comprehensively promote the development of open science.

Full Text

Analysis of the Relationship Among Open Science, Open Sharing, and Open Data

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Abstract

[**Purpose/Significance**] This paper aims to provide theoretical guidance for the practice of scientific data open sharing in China by clarifying the relationships among open science, open sharing, and open data. [**Method/Process**] Using normative analysis, this paper first 梳理 s and defines the definitions and

characteristics of open science, open sharing, and open data, and then analyzes the pairwise relationships and the overall relationship among the three concepts. **[Result/Conclusion]** Open science, open sharing, and open data form a trinity of logical relationships. Open data serves as the material foundation for open sharing and open science; open sharing acts as the bridge between open data and open science; and open science represents the ultimate goal of open data and open sharing. Different stakeholders need to make concerted efforts for open science in order to comprehensively promote its development.

Keywords: open science; open sharing; open data
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Introduction

As early as 2013, Neelie Kroes, Vice President of the European Commission, stated: "We are entering the era of open science" [1]. Today, "implementing the national big data strategy and promoting the opening and sharing of data resources" has been written into China's 13th Five-Year Plan. "Policy, technology, and infrastructure construction in scientific data open sharing" has remained a hot topic at the third and fourth National Scientific Data Conferences in 2016 and 2017. Currently, scholars have extensively discussed topics such as policies [2], benefits [3], resources [4], funding models [5], operational models [6], practical surveys [7], problems and obstacles [8], and countermeasures [9] regarding scientific data open sharing. However, the relationships among open science, open sharing, and open data have not yet been clarified. A deep and comprehensive understanding of these relationships is crucial not only for strengthening the theoretical foundation of scientific data open sharing but also for promoting its practical implementation.

1. Definitions of Open Science, Open Sharing, and Open Data

1.1 Definition and Characteristics of Open Science Michael Nielsen first proposed an informal definition of open science, viewing it as an idea that various forms of scientific knowledge should be openly shared in the early stages of the scientific discovery process [10]. Later, multiple definitions emerged. For instance, open science can be seen as a cumulative knowledge production mechanism through which scientists can draw upon knowledge obtained by previous researchers and provide their discoveries to future researchers [11]. Open science also refers to a scientific culture characterized by openness, where scientists can immediately and broadly share research results with users [12]. Additionally, it represents a new approach to scientific research based on collaboration and a new method of disseminating knowledge using digital technologies and collaborative tools [13]. In summary, open science is both a concept, culture, or environment that uses information and communication technology (ICT) tools

and platforms to openly share scientific research results, and a model or method for publicly and freely accessing scientific research results or conducting open collaborative research using ICT tools and platforms. Open science involves a series of issues throughout the open research lifecycle, with the most important being: (1) open access (OA); (2) open data; (3) free and open-source software; (4) reproducible research; (5) open peer review; (6) open science policy; (7) open funding; (8) open science evaluation; (9) open science tools; and (10) open education [14].

Open science has three main characteristics [15]: (1) **High degree of openness.** Open science exhibits an unprecedented level of openness compared to any previous scientific era. It emphasizes not only public participation in scientific research processes across temporal and spatial boundaries but also free and open access to various scientific data and research results, thereby achieving intelligent openness of scientific research content, processes, and infrastructure—meaning 同时具备可访问性 (accessibility), 可理解性 (intelligibility), 可评估性 (assessability), and 可用性 (usability). (2) **Socialization.** Open science heralds a new era of scientific research: the era of citizen science. It requires traditionally closed and implicit scientific research processes to become visible to the public while encouraging non-professionals to participate in scientific research, thereby transforming ordinary citizens who were previously excluded from science into important participants and enhancing public understanding of scientific research processes [16]. (3) **Sharing and collaboration.** Open science enables the latest research results to be freely shared and utilized worldwide in a timely manner, expanding the scope of knowledge dissemination, improving its efficiency, and accelerating knowledge innovation to maximize scientific benefits. Simultaneously, it helps researchers and institutions gain inspiration and wisdom from others, enhance research efficiency, and gain public recognition and academic influence, thereby transforming individual interests into common benefits that provide the original motivation for open sharing [17].

1.2 Definition and Characteristics of Open Sharing Although no authoritative definition of open sharing currently exists, the concept of sharing is well-known. Open sharing has two meanings: (1) In the traditional sense, it refers to the act of individuals or institutions providing relevant data, information, or works to society or users for utilization by others. This is a limited form of open sharing that does not emphasize free online access and use, similar to traditional book publishing. (2) In the modern sense, it refers to the act of individuals or institutions providing data, information, or works to society or users in the network environment and authorizing others to use them free of charge. Open sharing in the open science context refers to the second meaning. This type of open sharing is closely related to OA but cannot be completely equated with it, as OA is merely a primary method of open sharing. Other methods, such as open publishing based on personal or institutional websites and microblogs, also implement open sharing.

The main characteristics of open sharing are: (1) **Comprehensive openness**, meaning sharing based on the internet for all users rather than selective users; (2) **Free use**, meaning users can utilize open sharing resources completely free of charge; (3) **Diverse methods**, such as OA, open publishing, open storage, open citation, open reading, open review, and open creation; and (4) **Adherence to open sharing agreements**, such as Creative Commons (CC) licenses, Open Data Protocol (OData), and General Public License (GPL).

1.3 Definition and Characteristics of Open Data According to the Open Knowledge International organization, open data refers to data that anyone can freely use, reuse, and redistribute, subject at most to the requirements for attribution and share-alike [18]. Broadly speaking, open data includes open government data, open scientific data (or research data), open institutional data (such as corporate data), and open personal data. Among these, open scientific data refers to "scientific data that are freely available on the public internet, allowing any user to download, copy, analyze, reprocess, transmit them to software, or use them for any other purpose without financial, legal, or technical barriers beyond accessing the internet" [19]. Open data has three characteristics: (1) **Availability and accessibility**: Data must be available as a whole in a convenient and modifiable form at no more than reasonable reproduction cost, preferably through internet download. (2) **Reuse and redistribution**: Data must be provided under terms that permit reuse and redistribution, including mixing with other datasets. (3) **Universal participation**: Everyone must be able to use, reuse, and redistribute the data without discrimination against any field of endeavor, persons, or groups. For example, "non-commercial" restrictions that prohibit "commercial" use or restrictions that disallow use for certain purposes (such as education) are not permitted. However, data are truly open only when they satisfy both "technical openness" and "legal openness." "Technical openness" means data are available in machine-readable standard formats that can be retrieved and purposefully processed by computers, while "legal openness" means data are explicitly licensed in a manner that imposes no restrictions and allows both commercial and non-commercial use and reuse [20].

2. Pairwise Relationships Among Open Science, Open Sharing, and Open Data

The open science movement broadly includes the acquisition, dissemination, and reuse of publications, data, materials, and methods. It is closely related not only to the "open data" movement that promotes data sharing and the "open access" movement that promotes publication sharing but also to open-source intellectual property models, open governance, and scientific ethics [21]. To promote scientific data open sharing, it is necessary to understand the relationships among open science, open sharing, and open data.

2.1 Relationship Between Open Science and Open Sharing Open science and open sharing have a positive interactive relationship, and both are

important components of an open society.

2.1.1 Open Science's Promotional Effect on Open Sharing Because open science differs significantly from traditional science and is characterized by "complete openness," it can promote open sharing in three ways: (1) **Providing environmental support for open sharing.** As Library Director Wu Jianzhong pointed out, open science is the product of combining the concept of open access to academic resources with modern information and communication technology, aiming to promote the disclosure, opening, and reuse of academic achievements through modern technological means, thereby forming a research environment conducive to knowledge sharing, mass innovation, and economic development [22]. This research environment essentially provides "fertile soil" for cultivating open sharing and can effectively support open sharing practices. For example, the European Open Science Cloud developed by the European Commission aims to meet the urgent needs of the scientific community, increase data acquisition and reuse, and create a virtual environment for all European researchers to store, manage, analyze, and reuse data by pooling existing and emerging data infrastructures, thereby reducing the costs of data storage and high-performance analysis and promoting researchers' ability to openly share and analyze interdisciplinary and cross-national research data [13].

(2) **Providing platform support for open sharing.** Many organizations or institutions advocating open science have developed open science websites or platforms that greatly facilitate open sharing. For example, ScienceOpen is currently a freely accessible, interactive research communication platform with technical infrastructure supporting multi-dimensional search and discovery, community curation, and researcher networking. It provides an excellent open sharing platform for academic publishers, OA journals, university libraries, academic societies, research institutions, and individual researchers. It enables researchers to share their expertise through public review of any paper and receive recognition, create collections to advance their research fields, and use paper- and author-level evaluation metrics to promote their research and track readers, thereby helping individual researchers openly share their research processes and results and expand their academic influence [23].

(3) **Providing resource support for open sharing.** Open science encompasses multiple aspects, with core elements including OA journal articles, OA books, open data, open source code, open notebooks, open standards, open software, open systems and tools, open institutional repositories, and open disciplinary repositories. These provide inexhaustible resources for open sharing. For example, ScienceOpen currently offers search and utilization of over 50 million OA articles and article records [23]. Additionally, open science research means more partners participate in research activities (providing more human resources for open sharing), such as InnoCentive, which leverages collective wisdom to help organizations of all

sizes solve critical business, scientific, and technological problems and is a pioneer in global crowdsourced innovation [24].

2.1.2 Open Sharing's Promotional Effect on Open Science Although the Royal Society emphasized when founding *Philosophical Transactions* in 1665 that all new discoveries should be disseminated as widely as possible, and open science had already become a European tradition in the Middle Ages [17], traditional open science did not embody the concepts of "freedom, openness, collaboration, and sharing." For a long time, open science faced significant personal and systemic barriers. Personal barriers mainly manifested as concerns about free-riding, requiring additional time and effort, difficulties with digital tools, challenges in ensuring data privacy, and reluctance to share code. Systemic barriers included lack of legal support for open sharing, absence of standards for sharing research materials, cultural and institutional constraints, ineffective policy guidance, open costs, and evaluation standards that hindered openness [25]. However, with the rise and rapid development of the OA movement and open data movement in the 21st century, modern open science, adhering to the principles of "freedom, openness, collaboration, and sharing," has truly entered the historical stage. The tremendous progress achieved in science today is the result of both individual researchers' efforts and their willingness to share their work. Open sharing plays an extremely important role in promoting open science:

First, **sharing enables research to progress faster and further.** This is because: (1) Sharing provides a knowledge foundation. As Isaac Newton said, "If I have seen further, it is by standing on the shoulders of giants" [26]. This phenomenon holds true for any successful scientist. By sharing results and ideas, researchers can build upon the work of predecessors. Without connection to others' work, a continuous research enterprise would be unimaginable. (2) It broadens research scope. Learning from others' work allows individuals to specialize while ensuring expanded collective achievements. In many scientific fields, the sheer volume of knowledge and complexity of methods make it impossible for individuals to possess all skills needed for a research question. When scientists share their expertise or research results, the collective work progresses faster and deeper. (3) It diversifies perspectives. Broader access to ideas, data, and unique resources increases contributions from individuals at resource-limited institutions, expanding both the number of researchers who can study a topic and the diversity of the field. Assuming a person's professional background determines their worldview and interpretation, the diversity of scientists in turn affects the questions investigated, methods employed, and applications of final results, helping find solutions to previously intractable problems.

Second, **sharing enables more efficient resource utilization.** This is because: (1) Sharing reduces costs, including money and effort. It decreases opportunities for researchers to conduct identical experiments, thereby reducing required funding and research costs, though some duplication is essential for

scientific progress. (2) It maximizes data utilization. A large-scale survey may involve thousands of subjects studied over many years. While initially used to test one variable's effect, the data can help explore many other issues. Placing these data in a publicly accessible repository allows other researchers to "mine" them, potentially generating additional publications. (3) It corrects analytical errors. In some cases, broader dataset access may produce not only new discoveries but also corrections to old data, as errors can occur in data analysis and interpretation—such as authors misjudging experimental particularities, using inappropriate statistics, or failing to acknowledge subject group biases. Data sharing helps others discover and correct these errors. (4) It increases survey impact. When resources used in published reports are subsequently utilized in others' research, the original paper may receive more attention, expanding its influence. Studies show that sharing detailed cancer microarray clinical trial data increases original authors' citation rates by 69% [27]. This increased citation may further strengthen the influence of resources used in the original research. (5) It promotes resource development. Merging datasets may trigger the creation of more comprehensive databases than any single laboratory could develop, allowing more comprehensive reflection of investigated phenomena and potentially enabling testing of more complex model systems.

Third, **sharing enhances the scientific community atmosphere.** This is because: (1) Sharing discourages fraud and builds confidence. When sharing is the norm, misconduct is less likely as researchers know others may attempt to replicate their work. Unwillingness to share may also suggest someone is hiding something. (2) It boosts creativity. A core characteristic of science is an open atmosphere, and sharing ideas and resources helps create this transparent environment. Open information exchange may also generate new ideas through cross-pollination of multiple people's thoughts [28]. Thus, open sharing becomes the key to unlocking open science. For example, the Biodiversity Heritage Library (BHL) uses extensive partnerships, curated content, innovative tools and services, and data accessibility to create an open scientific resource that drives scientific progress through linking, use, and reuse. Currently, BHL provides free and open access to over 46.6 million pages of digitized texts and grey literature on biodiversity to scientists, scholars, citizen science workers, and the public, covering more than 97,000 titles and 163,000 volumes—approximately 17% of biodiversity literature [29], significantly advancing open scientific research on biodiversity.

2.2 Relationship Between Open Science and Open Data Open science and open data are closely connected, with their relationship 主要体现在如下两方面:

2.2.1 Open Science as Support and Guarantee for Open Data Open science can provide conceptual support and guarantee for open data operations. The philosophy of "freedom, openness, collaboration, and sharing" in open science serves as an important basis for international organizations and national institutions to formulate relevant scientific data open sharing policies, which

in turn guide and directly support or influence specific open data activities. For example, adhering to open science principles, the OECD issued the *Principles and Guidelines for Access to Research Data from Public Funding* in 2007 [30], establishing 13 principles for research data open sharing. These principles have become important references for OECD countries to adjust or formulate open data legal provisions. Moreover, as open science is an open scientific research and communication model based on the internet—"Science 2.0"—it can fully utilize Web 2.0 technologies and tools such as blogs, wikis, online communication websites, and media sharing platforms, enabling people to not only passively access information unidirectionally but also edit, publish, and categorize information, breaking spatiotemporal constraints to communicate and share with different objects anytime and anywhere [31], thereby providing technical support and assurance for open data operations.

2.2.2 Open Data as a Key Element of Open Science Researchers have found that among the nine elements essential to scientific openness is "the existence of databases and knowledge repositories for data, materials, software, and models" [21]. In other words, open data constitutes an important component of open science. Today, open data is increasingly important in social and economic development. The McKinsey Global Institute found that open data can unlock $3.2 trillion to $5.4 trillion in economic value annually across seven sectors: education, transportation, consumer goods, electricity, oil and gas, healthcare, and consumer finance [32]. In certain fields, open data and its sharing have particularly significant social and economic value. For example, after NASA's Earth observation satellite images of the Earth's surface environment became freely available via the internet, they generated enormous scientific benefits, not only facilitating geological surveys but also enhancing international cooperation impact and participation. It is estimated that this created an annual environmental management industry value of $935 million, with direct benefits to the U.S. economy exceeding $100 million annually, while promoting application development by many companies worldwide [15].

2.3 Relationship Between Open Sharing and Open Data The relationship between open sharing and open data is mainly reflected in two aspects:

2.3.1 Open Data as an Important Object of Open Sharing From the perspective of information and knowledge exchange, people have long emphasized literature sharing or literature-based information sharing while relatively neglecting data sharing. The OA movement broke traditional information exchange patterns, making open data gradually become the material foundation and important object of open sharing. This is because the utilization of open data is increasingly important, and various public institutions face pressure to release raw data covering numerous fields such as transportation, weather, geography, tourism, statistics, commerce, food, safety, education, and the public sector. Open data compensates for the traditional separation between public

institutions and users. Open access to publicly funded data can yield greater public investment returns, create wealth through downstream product use, provide decision-makers with data needed to solve complex problems [33], and help citizens participate in analyzing large datasets.

However, open data must dispel four myths [3]: (1) **Data publication will automatically generate benefits.** Some believe that publishing data itself can create or even enhance competitive advantages. However, open data faces many obstacles and requires infrastructure support; we cannot expect the public to possess the same knowledge and capabilities as researchers. Therefore, lowering the knowledge threshold for data use is necessary to maximize value through large-scale data utilization. (2) **All information should be published without restriction.** Certain data may be unsuitable for open sharing for special reasons, including privacy legislation, poor data quality, overly complex and incomprehensible data structures, or explicit legal prohibitions. (3) **It is simply a matter of releasing public data.** While some policymakers prefer simply providing data or mistakenly believe data are readily available, source data often cannot be used immediately because they require quality assessment, modification, and processing; relevant metadata may be unavailable, making data difficult to find; or feedback mechanisms for open data use effects may be lacking. (4) **Everyone can use open data.** This fallacy assumes open data users have the resources, expertise, and capabilities to utilize data, which is not true, as many users are unclear about how to use open data or face many obstacles in doing so.

2.3.2 Open Sharing as the Best Dissemination Method for Open Data
Individuals or institutions can achieve global dissemination and utilization of open data through various open sharing methods such as open access, open publishing, and self-media platform release. Open sharing is the best dissemination method for open data because it offers wide and fast dissemination at much lower cost than print media or library storage. Preservation and reuse costs may also be lower than recollecting data, thus maximizing return on investment in open data development. Additionally, open sharing enables one-to-many dissemination of open data in a radiating pattern. Mandatory open sharing of data also helps prevent or expose scientific misconduct and is crucial for addressing global societal issues such as climate change, public health, and biodiversity loss. Consequently, many international and intergovernmental organizations and funding agencies—such as the OECD, International Council for Science, UNESCO Intergovernmental Oceanographic Commission, Global Biodiversity Information Facility, European Research Council, UK Research Councils, U.S. National Science Foundation, and National Institutes of Health—have formulated scientific data open sharing policies. Some journals, including *Science* and *Nature*, explicitly expect data to be publicly accessible and list appropriate knowledge repositories for certain data types [34].

3. The Trinity Relationship Among Open Science, Open Sharing, and Open Data

Open science, open sharing, and open data have inherent interconnections (see Figure 1 [Figure 1: see original paper]). This is reflected in three aspects:

(1) **Open data is the material foundation of open sharing and open science.** As an extremely important type of open resource, open data—along with open access journals, papers, books, video and audio materials, and other multimedia resources—constitutes the material source for open sharing. Particularly in the open science environment, sharing data is a routine practice in scientific research with widely accepted and obvious benefits [35]. These include promoting economic growth and job creation; improving public service efficiency and coverage; enhancing transparency, accountability, and citizen participation; promoting better information sharing within government [36]; strengthening open scientific research; promoting interdisciplinary, cross-sectoral, cross-institutional, and international research; encouraging diversity in analysis and opinion; supporting automated knowledge discovery tools in online applications; enabling verification of previous results; allowing testing of new or alternative hypotheses and analytical methods; supporting research on data collection methods and measurements; enabling exploration of topics unforeseen by researchers; allowing creation of new datasets, information, and knowledge through data combination; helping maximize the research potential of new digital technologies and networks; providing greater returns on public research investment; promoting education of new researchers; and delivering factual information to developing countries and promoting capacity building [4]. Consequently, since 2013, global scientific institutions including the European Commission, U.S. Office of Science and Technology Policy, and Global Research Council have formulated policies supporting public open access to scientific data. Some charitable organizations, including the Bill & Melinda Gates Foundation and Wellcome Trust, also require their grant recipients to provide open data. As Carly Strasser, head of the Data-Driven Discovery program fund, stated, "Open science, data sharing, and software sharing are the future of science; without openness, doing science will become more difficult." The average data sharing rate for articles in the journal *Psychological Science*, which uses open data badges, reached 38% from 2013 to 2015—an increase of 10 times [37], further demonstrating that open data can significantly promote open science development.

(2) **Open sharing is both the bridge connecting open data and open science and the technical means to move from open data to open science.** Today, various open sharing behaviors—such as promoting open access to research publications, open utilization of research data, open-source software and open standards, and open documentation of research processes—are concrete practices leading to open science [38]. Particu-

larly, open data can only be freely accessed and widely utilized by stakeholders through open sharing, thereby fully leveraging its functions and utilities to help achieve open science goals. Thus, open sharing builds a bridge between open data and open science, enabling the transition from open data to open science. Moreover, various open sharing technologies—such as Web 2.0 technologies (blogs, wikis, Twitter, Facebook, RSS, tags, bookmarks), open-source software (LibreOffice, GNU Image Manipulation Program), MOOCs, network self-publishing platforms (e.g., Bookrix), and cloud computing tools (e.g., ownCloud, Nextcloud)—all support open data and open science. Additionally, open sharing can provide open data through at least three channels: data repositories, data journals, and data description documents in academic journals [39].

(3) **Open science is the ultimate goal of open data and open sharing, with interactive relationships between them.** On the one hand, as discussed above, open science is influenced by open data and open sharing; to promote scientific progress, we need openness and sharing [40]. On the other hand, open science can react upon open data and open sharing through policies, models, technologies and methods, and environment. For example, open science policies can regulate and guide open data and open sharing behaviors; open science models can guide open data and open sharing methods; open science technologies can provide technical support; and open science environments help shape organizational open sharing cultures. The direct goals of open data and open sharing are to help researchers obtain benefits such as [41]: (1) enabling low-cost or free publication of scientific research results and increasing citations of open publications; (2) increasing media coverage of open publications; (3) obtaining awards and special funding to enhance researchers' or institutions' scientific levels; (4) helping researchers gain support from open research institutions, discover new projects and collaborators, and improve research quality. Ultimately, these benefits promote open science development. In other words, open science is the ultimate goal of open data and open sharing.

In summary, open science, open sharing, and open data form a trinity of logical relationships, wherein open data is the material foundation, open sharing is the bridge, and open science is the ultimate goal. Clarifying these relationships has extensive practical value for promoting open sharing and open science. First, it helps enhance awareness of open data and open sharing. Today, openness has become a global consensus, and the open movement characterized by knowledge sharing has continuously deepened from open access to open data to open science, triggering transformations in scientific research paradigms and knowledge exchange ecosystems [22]. However, while scientific workers often recognize the potential of open research data, most remain silent about the openness of their own data [42]. Surveys show that although 75% of people are willing to share their data with others, only 36% actually make their data easily accessible [43], indicating that people have not yet recognized the important value and role

of open data and open sharing. The path to open data, open sharing, and open science remains long. Therefore, we need to widely publicize the importance of open sharing and open science and strengthen specialized education in open data and open access, such as offering courses on "Open Data," "Open Access," or "Open Science" at universities. Second, it helps advocate for active stakeholder participation in open science practice. When people recognize the significance of open science and open sharing, they will actively participate in open science practice and take corresponding actions: scientists should communicate data and models they collect and create through open access; universities and research institutions should play important roles in supporting an open data culture by making researcher data exchange an important criterion for career development and compensation; research evaluation should reward open data and collaboration as much as journal articles and other publications; academic societies, institutions, and professional organizations should promote open science work among members and find ways to provide continuous funding support for OA journals; research councils and charities should improve communication of research data from funded projects by identifying who can maximize data utilization, providing data and metadata management costs, and collaborating with others to ensure dataset sustainability; scientific journals should gradually increase requirements for traceable and usable data in papers; industry sectors and relevant regulatory departments should collaborate to identify methods for sharing data, information, and knowledge that benefit the public; and governments should formulate open science data policies [15].

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Note: Figure translations are in progress. See original paper for figures.