The Varying Openness of Digital Open Science Tools

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Abstract

Digital tools that support Open Science practices play a key role in the seamless accumulation, archiving and dissemination of scholarly data, outcomes and conclusions. Despite their integration into Open Science practices, the providence and design of these digital tools are rarely explicitly scrutinized. This means that influential factors, such as the funding models of the parent organizations, their geographic location, and the dependency on digital infrastructures are rarely considered. Suggestions from literature and anecdotal evidence already draw attention to the impact of these factors, and raise the question of whether the Open Science ecosystem can realise the aspiration to become a truly "unlimited digital commons" in its current structure.

In an online research approach, we compiled and analysed the geolocation, terms and conditions as well as funding models of 242 digital tools increasingly being used by researchers in various disciplines. Our findings indicate that design decisions and restrictions are biased towards researchers in North American and European scholarly communities. In order to make the future Open Science ecosystem inclusive and operable for researchers in all world regions including Africa, Latin America, Asia and Oceania, those should be actively included in design decision processes.

Digital Open Science Tools carry the promise of enabling collaboration across disciplines, world regions and language groups through responsive design. We therefore encourage long term funding mechanisms and ethnically as well as culturally inclusive approaches serving local prerequisites and conditions to tool design and construction allowing a globally connected digital research infrastructure to evolve in a regionally balanced manner.

Introduction

The evolution of the Open Science ecosystem

Open Science encompasses a collection of activities, principles and tools oriented at making scientific research accessible to all levels of society proposed to increase transparency and efficiency in research workflows and scholarly publishing (Rahal and Havemann, 2019). Open Science activities are clustered around a number of areas of action, including Open Data, Open Access (OA), Open Educational Resources (OER), Free and Open Source Software (FOSS), Open Hardware, Open Methodologies and Open Peer Review, including the growing Citizen Science movement and broader societal engagement.

The Open Science movement has garnered support from both individual researchers as well as high-level policy and funding around the world and given rise to a range of influential regional high-level and grassroots initiatives alike in Africa[1], IberoAmerica[2],

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[1] Africa: http://africanopenscience.org.za/; https://info.africarxiv.org/; https://savoirs.cames.online/jspui/, http://africaosh.com/

[2] Ibero America: http://amelica.org/index.php/en/home/; https://www.redalyc.org/; https://scielo.org/ ; http://mutabit.com/grafoscopio/index.en.html

North America, Europe[3], North America[4], Asia[5] and Oceania[6] as well as several independent and cross-regional networks and community initiatives[7]. The global scientific community is increasingly recognizing the benefits of learning from each other and aligning technically feasible approaches adopted to regional infrastructure prerequisites. At the same time, research communities are contributing to the development of resources, practice change and activism to establish Open Science and incorporate it into mainstream research workflows; The Open Science MOOC, FOSTER Open Science and the Open Scholarship Knowledge Base (OSKB) are just a few of many examples[8]. The oldest and most visible of these communities are within Free and Open Source Software (FOSS) development (Powell, 2012). In recent years, community activities are extending to a wide range of areas, including community-driven and often volunteer-run preprint repository platforms,[9] open peer review services,[10] and capacity building programs and training resources.[11] These wide-ranging activities are united under core values, such as openness, equitable sharing, access to resources and optimized re-use (Tennant *et al*., 2019).

The ongoing COVID-19 pandemic has drawn attention to the key role of openness in research (OECD, 2020). Widespread commitment to openness in COVID-19 research by funders, governments, research institutions and individual researchers has showcased the impact of rapid OA publishing, open data sharing and the open and

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[3] Europe / EU: https://ec.europa.eu/research/openscience/index.cfm; Germany: https://www.osc.uni-muenchen.de/toolbox/index.html

[4] North America / USA: https://www.cos.io/; https://our-research.org/; Canada: https://pkp.sfu.ca/ops/

[5] Asia / Indonesia: https://rinarxiv.lipi.go.id/lipi; India: https://indiarxiv.in/; Japan: https://openscience.jp/

[6] Oceanio / Australia: https://www.freeourknowledge.org/

[7] Cross-regional: https://opensciencetools.org/; http://openhardware.science/;

[8] For example, https://opensciencemooc.eu/, https://www.fosteropenscience.eu/, https://www.oercommons.org/hubs/OSKB

[9] For example, https://osf.io/preprints/; https://www.preprints.org/ - and for an overview of biological-focused pre-print archives see https://asapbio.org/preprint-servers

[10] For example, https://prereview.org/, https://peercommunityin.org/

[11] For example, www.fosteropenscience.euhttps://asapbio.org/preprint-servers

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collective design of hardware (Maia Chagas *et al.*, 2020; Zastrow, 2020).[12] All of these areas have underscored the importance of open research practices as a means to increase efficiency and speed of information sharing. This has been vital not only for medical research, but also for policy makers and practitioners in responding to the impact of COVID-19 on society.

Digital tools supporting Open Science activities

The increasing support for open research activities provides an opportune moment for critical reflection on the Open Science movement so far. In particular, it prompts a critical assessment of the evolution of the digital infrastructures, tools and online working practices that underpin open research activities. Of these different areas, the design, deployment and use of the digital tools that support Open Science activities are the least scrutinized. Indeed, critical evaluations of the evolving landscape of interlinked digital tools supporting Open Science are scarce (Kramer and Bosman, 2016).

Digital tools are a ubiquitous part of Open Science. Most steps of the research workflow are nowadays complemented or replaced by online applications. These tools assist researchers to share and collaborate, and thus increase openness and transparency at all stages of the research lifecycle. Many of these tools have changed the way that research is done and how research resources – including datasets, publications, educational resources and software – are circulated globally (Kramer and Bosman, 2016).

In this paper, we collectively term these tools "Digital Open Science Tools" (DOSTs). This category encompasses the wide range of digital tools that are involved in

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[12] https://www.eurekalert.org/pub_releases/2020-08/hl-crr081220.php and http://www.oecd.org/coronavirus/policy-responses/why-open-science-is-critical-to-combatting-covid-19-cd6ab2f9/ , https://asapbio.org/preprints-and-covid-19

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facilitating openness during the research lifecycle. In this paper, the term 'DOST' includes any digital tool (for-profit, non-profit and community-led entities) used in open research, irrespective of whether they were designed explicitly for Open Science or have been co-opted into Open Science practices.

Growing efforts to promote interoperability and open workflows have made interconnection key to the success of any DOST (Wilkinson *et al.*, 2016). The interconnection of tools and the interoperability of their outputs enable users to move between tools at different stages of the research lifecycle to facilitate research, data dissemination and publication. The interconnectedness of the tools, as well as the overlaps in their function within the DOST landscape ("multiplicity"), means that multiple "pathways" exist for data to progress through a research lifecycle (see figure 1). How these "pathways" are selected depend on a variety of issues such as user preference, access to specific DOSTs, demands of the research project and preferences of the research community.

[Figure 1]

New tools are continually being added to the DOST landscape, and new connections between tools are regularly emerging to populate this ecosystem. We use the term "ecosystem" in contrast to the more common "landscape" to designate the dynamism of the online environment as an interconnected system through which resources move. We ground this understanding in biological understandings of ecosystems as biological communities of interacting organisms and non-living components that interact as a system. This DOST ecosystem is dynamic, multiplicitous and subject to internal and external pressures. It includes interconnected/interdependent DOSTs, as well as the information and communication infrastructures, communities of users and socio-political

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stakeholders. Internal and external pressures from these actors determine the persistence of the DOSTs and the structure of the ecosystem.

The underlying dynamics and influences within the evolving DOST ecosystem have been extremely influential in driving forward the Open Science movement as a whole. Tools within the ecosystem, such as GitHub, are changing the way collaborations are managed. Publishers like PLoS and F1000 are redefining transparent publishing models, and repositories such as Zenodo, OSF and dSpace are offering open platforms for sharing and re-using data.

The constantly growing uptake in usage of DOSTs, and their increasing interconnectivity and interoperability may give the impression that the digital landscape of Open Science is positively unfolding and developing to support the growing needs of the Open Science community. Widespread endorsement of many DOSTs, support from socio-political actors and the rapid organization of "user communities" associated with specific tools has left little time for critical reflection on how the ecosystem is evolving and what power dynamics are shaping its evolution. How, it is increasingly being asked, do the tools developed by multiple scholarly for-profit service providers, non-profit organizations and open source communities contribute to the Open Science vision and mission to make research workflows and results accessible to all sectors of society across the globe?

In this paper we critically interrogate the DOST ecosystem. We ask how its current structure enables knowledge availability and question whether social, political or economic barriers linked to DOST design and deployment undermine this objective. To do so, we ask three main questions of the ecosystem and its actors:

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1. What is the impact of a small number of countries dominating DOST design and deployment?

2. Do heterogeneities in values, funding, and stakeholders that influence tool design and interconnection affect the openness of the DOST ecosystem?

3. How (if at all) are external power dynamics and influences recognized and addressed in the DOST ecosystem?

The subsections below provide a short background to these three questions, and frame the empirical data presented in the following sections.

Geographic distribution of DOSTs and user communities

The Open Science movement supports the democratization of research resources. Increasing openness in research will make resources available to all individuals in all nations and at all levels of society[13]. In this way, Open Science promotes equitable access to resources through the (self-described) model of the "knowledge commons" (Hess and Ostrom, 2007) which promotes a form of direct democracy, where every individual has the right---and ability--to access information, data, and content that is collectively owned and managed by a community of users. While this direct democracy model works well as a model of resource distribution, it complicates the evolution of the DOST ecosystem. The distribution of researchers and resources around the world is unevenly weighted towards a small number of high-income countries (HICs). A 2013 report by UNESCO highlighted that China, the European Union, Japan, the Russian Federation and the USA together accounted for 72% of researchers worldwide. Unsurprisingly, the evolution of DOSTs reflects this distribution, with the majority of tools being developed in countries with a high density of researchers and considerable

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[13] https://en.unesco.org/science-sustainable-future/open-science

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investment in research and national digital infrastructures. As a result, the design of the tools and the evolution of user communities – as dictated by the majority of users – is weighted in favour of a small number of countries.

The specific geographic location of many DOSTs, as reflected by the location of their development, registration and hosting, contrasts to the approach championed by the Free and Open Source Software (FOSS) movement. FOSS has long been calling for and implementing a more representative form of democracy for software development and distribution by promoting models that avoid specific geographically-clustered nodes (Vermeir *et al.*, 2018; Tennant *et al.*, 2020). This model of "software mirrors"[14] is commonly used in systems such as GNU as well as Linux distributions like Debian and Fedora. Nonetheless, and likely due in part to economies of scale, this approach of mirroring services to increase access has not been replicated within the DOST ecosystem.

Heterogeneities in purpose and design of DOSTs

The Open Science movement promotes widely agreed values that also define good scientific practice. These include openness, credibility, reproducibility, and verifiability of any research output (Bartling and Friesike, 2014). Nonetheless, the endorsement of these core values can cause the widespread value/practice-heterogeneity within the Open Science movement to be overlooked. Indeed, Open Science can be thought of both as a practice and as a philosophy (Levin *et al.*, 2016), implying that the motivations for individuals to get involved can vary considerably (Fecher and Friesike, 2014).

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[14] A software mirror is a server that provides an exact copy of data from another server. These mirrors can be held in different geographic locations and are intended to provide fault tolerance, or a means of redundancy in case something goes wrong with the primary or "principal" server.

Fecher and Fiesike (2014: 17) mention five different Open Science schools of thought: The *infrastructure school* (which is concerned with the technological architecture), the *public school* (which is concerned with the accessibility of knowledge creation), the *measurement school* (which is concerned with alternative impact measurement), the *democratic school* (which is concerned with access to knowledge) and the *pragmatic school* (which is concerned with collaborative research). It can thus not be assumed that everyone is motivated to a similar degree by the core values. A number of pragmatic reasons also play important roles in the uptake of Open Science practices and tools, including efficiency, career advancement, journal and institutional requirements and community expectations (Ferguson, 2014).

This heterogeneity is further complicated by the number of actors within the DOST ecosystem. The unrestricted development of DOSTs has caused this space to be populated by stakeholders ranging from community projects to commercial companies. These different actors may have highly variable reasons for developing the DOSTs, and rely on highly disparate funding sources to ensure their longevity. While some DOSTs are explicitly designed to further open research practices, some may be a commercial venture responding to a gap in the market. Indeed, the highly variable development of DOSTs has led to the uncoordinated evolution of the DOST ecosystem, meaning that the financial, governmental and infrastructural influences are poorly understood.

The ways and reasons through which user-communities are recruited around DOSTs – as with any form of technology – are similarly diverse. These may range from bottom-up community endorsement, advertising, integration with other DOSTs or commercial endorsement. The persistence of a DOST within the ecosystem can thus depend on a range of different reasons, including accessibility, ease of use, visibility through

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advertising and promotion, or simply that the size of the user community allows it to dominate similar DOSTs (Mody, 2011).

Recognizing the heterogeneity inherent in the motivations for creating DOSTs and recruiting user communities is critical. It negates the assumption that endorsement from members of the Open Science community means that the tool is designed or deployed to optimally promote the values of the Open Science movement. To the contrary, the persistence of certain DOSTs over others depends as much on market forces and user preferences as on alignment with Open Science values.

External power dynamics

Research occurs within highly complex networks of power and influence of financial, governmental and societal actors (Vermeir *et al.*, 2018). As discussed above, the DOST ecosystem, while digital, relies on funders, hosts and infrastructures that are very much located in the physical world. DOSTs are thus subject to national legislation and regulation. Moreover, the ecosystem relies on information and communication infrastructures that are neither open nor designed with openness in mind. Service providers, content delivery networks, and cloud storage facilities, for example, are largely user-agnostic and operated by large international companies, yet are becoming extremely influential in the construction of the DOST ecosystem.

A complex ecosystem of digital heterogeneity

The rapid and diverse evolution of DOSTs has caused an exponential expansion of the ecosystem. In this dynamic space, researchers are continually provided with more options for integrating openness into their daily research workflow. Nonetheless, the

rapid expansion of DOSTs and their insertion into the Open Science ecosystem requires careful scrutiny. At present, there is little critical examination of what tools are integrated into–and persist in–this ecosystem, what forces/values/preferences dictate how they are connected, why they are used, and what underlying infrastructures are being endorsed/supported by their presence within the DOST ecosystem.

Recognizing such concerns makes it apparent that the DOST ecosystem cannot be taken as *de facto* open, equitable and transparent. The range of actors and the interconnectivity of the tools makes it likely that there are a range of barriers that hamper certain users from engaging both in the tools and the workflows that they are embedded within. Key considerations include:

- Tools may be uncritically integrated into the ecosystem causing existing power dynamics to be perpetuated, leading to the marginalization of certain user groups

- Governments and commercial companies have undue influence on the landscape due to their hosting, financing, and otherwise influential roles

- The existing DOST ecosystem may become prescriptive of a specific way of "doing", as one tool becomes hyper-dominant

Table 1 adapts the concept of "data assemblages" developed in Critical Data Studies for use in outlining the DOST ecosystem. Data assemblage refers to the technological, political, social and economic apparatuses and elements that constitute and frame the generation, circulation and deployment of data (Kitchin and Lauriault, 2014). Just as data assemblages map the complex set of stakeholders and pressures that influence the production, dissemination and reuse of data, Table 1 highlights some of the key pressures on the DOST ecosystem and their potential impact on the evolution of these spaces.

[Table 1]

To our knowledge, there have not yet been attempts to provide an overview of how the DOST ecosystem shifts and adapts to these pressures. Indeed, the heterogeneity not only of the ecosystem, but also the actors and pressures that influence it, make this a challenging task. This paper presents a methodological attempt to map a selection of the DOST ecosystem including links between the tools. Our intention is to generate an interactive map of the DOST ecosystem so as to be able to test pressure and tipping points that shape ecosystem make-up and functioning.

Methodology

DOSTs were identified from a range of different sources, including previous studies on DOSTs,[15] extended web searches and tools foregrounded in key Open Science communities such as the Research Data Alliance and the Open Science MOOC and compiled into a database. As mentioned in the introduction, we used a very broad definition of DOSTs and included commercial, non-profit and community-driven digital tools that are currently used in open research. We did not make the availability of source code a prerequisite for inclusion. Neither did we limit the tools to those provided free to users.

This database was ordered according to the criteria outlined in section below. We developed the categories based on our analysis of ecosystem pressures presented in table 1. The information used to populate these categories was freely available on the respective websites, each of which was examined by both of authors. Database entries

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[15] https://101innovations.wordpress.com/ and https://jrost.org/ (accessed 17 June 2020)

were cross-checked by the authors in duplicate. Discrepancies were discussed until consensus was reached. Using the network mapping criteria above, a database was developed for analysis.

The paper is based on the 3 September 2020 version of this database that can be accessed a https://zenodo.org/record/4013812#.X1D-FnlKjIU. It is anticipated that the database will continue to evolve with community input. Contributions to the evolving database are encouraged through communication with authors.

Sorting criteria for DOST database

In this paper we examine the current dataset which includes 242 DOSTs focusing on the information about language, T&Cs, Host institution, and sponsor or funding institutions. The columns in the dataset display the sorting criteria that were applied as follows:

Workflow step: At what point(s) during the research workflow is the tool primarily used? – *Discovery, Analysis, Writing, Publishing, Outreach, Assessment*[16]

Open Science category: Which subsection of the Open Science movement is the tool most closely related? – *Open hardware, Open educational resources, Open methodology, Open access, Open data, Open peer review, FOSS (free and open source software), Open lab notebook, Open Science [general category for multi-purpose tools].*

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[16] Workflow steps as defined by Bianca Kramer and Jeroen Bosman from the University of Utrecht. http://innoscholcomm.silk.co/page/Workflows. Accessed 20 March 2020.

Host (where applicable): Is the tool hosted by an organization other than itself? – *Named organization, otherwise 'Self', i.e. self-hosted*

Location / host location: In which world region is the tool or host located or registered? – *US (United States of America), UK (United Kingdom), EU (European Union), other|specific country, unspecified*

Language: What interface and description language is offered by the tool? – *Named language*

Funding source: How is the tool funded? – *Commercial, Various commercial, Grant, Various grant, Various mixed [commercial and grant], Institution*

Type of entity: How are the tool activities governed? – *NPO, Host affiliated, Commercial, Independent*

User fee: Does the tool require a fee to use all or part of its services? – *Free, Freemium, Membership fee, Services fee, APC*

Terms and Conditions: Are users in specific countries prohibited to use the tool? – *Explicit prohibition, Flags possible problems, No terms of use given, None mentioned*

Disclaimers

While the database produced provides an extensive list of OS tools, it is by no means exhaustive. By making the database an open resource we anticipate that it will be continually discussed and updated, both by ourselves and other practitioners in the field. In this way, the DOST dataset may become a reference resource for the Open Science community for digital tools development and optimization.

From figure 3 below it becomes apparent that most of the tools included in the database have been developed in Anglophone countries with English interfaces. The authors

recognize this linguistic bias and are committed to working with Open Science community members from various linguistic communities to make the future iterations of the database more representative of the global scholarly community and tools available.

Finally, it was not possible to map all the existing institutional repositories due to their high numbers and transitional states and unclear or lacking institutional affiliations. The repositories represented in the database are hosted and maintained by NGOs or small companies. It is anticipated that institutional repositories can be added over time by community crowdsourcing.

Results

Visualization of dataset

An interactive visual map of the 242 DOSTs was generated in Kumu. The interactive plot can be viewed here: https://kumu.io/a2p/dost. The Kumu software allows users to sort the data according to any of the sorting criteria discussed above. Figure 2 below illustrates the distribution of DOSTs according to research workflow steps. As can be seen from this figure, DOSTs actively contribute to all stages of research, but are particularly concentrated around analysis of data and publication.

[Figure 2]

Geographic distribution of tools and host organizations

The majority of DOSTs included in the database were explicitly connected to specific countries and regions. The geographic location of the DOST was available on the web

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pages through contact details, named host institutions or details of registration in the terms and conditions (T&Cs). Eighteen (18) of the listed tools did not give a specific geographic location on their websites.

As can be seen from figure 3 below, a high proportion of DOSTs available to the international research community are registered in (or linked to) the United States. It is therefore likely that the design and deployment of many of these tools was influenced by the needs and preferences of High Income Countries (HICs) researchers. Of the tools linked to a specific country, the vast majority were connected to the United States, either as a registered non-profit organization (NPO 501(c)3), a registered commercial company or hosted by a US American institution such as a university or government body. Others were also hosted by parent organizations, such as the Centre for Open Science, Wikimedia Foundation or GitHub. The numerical distribution of the countries hosting DOSTs is demonstrated in figure 3.

[Figure 3]

Financial models

[Figure 4]

There was considerable heterogeneity in the financial models of the DOSTs within the database. In an attempt to simplify this heterogeneity, the tools were classified into the categories *Commercial*, *Grant*, *mixed* (commercial and grant), and *Institutional*. The distribution of these funding models is visualized in figure 4. Half of the DOSTs used a

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mixed model of funding, combining grants, commercial support, membership fees, freemium models, consulting or crowdsourcing.

The geographic location of the DOSTs (figure 3) and the variations in funding (figure 4) together highlight how the DOST ecosystem is governed by a complex network of financial legislation. NPOs and commercial entities are subject to the respective national legislation governing financial transactions. Similarly, if tools are hosted by an NPO, academic institution or governmental organization they are subject to the legislation governing the host organization.

The complexity of the underlying funding mechanisms has significant implications for the DOST ecosystem. In particular, it complicates efforts to make the DOST ecosystem transparent with regards to funding sources and legislative influence. It also impacts on the financial viability and longevity of the DOSTs within the ecosystem. Indeed, the reliance of many DOSTs on crowdsourcing and time-limited grants means that many will struggle to achieve financial independence and sustainability.

Highly influential actors

We have documented selected interlinkages between the DOSTs in the database which can be viewed using the link https://zenodo.org/record/4013812#.X1D-FnlKjIU). From the analysis of the database it became apparent that certain entities are highly interlinked within the DOST ecosystem, such as GitHub, Center for Open Science and Digital Science. Figure 5 below details 8 highly influential organizations within the DOST landscape, demonstrating how these organizations/institutions are linked to DOSTs operating throughout the research workflow.

[Figure 5]

As shown in figure 5, 80.9% of the DOSTs in the database are linked to one or more of these 8 entities. These interlinkages were diverse and included direct sponsorship, hosting of the DOST, or the hosting of DOST resources. These interlinkages can also be visualized in the kumu plot at https://kumu.io/a2p/dost.

Variations in Terms & Conditions

Examination of the Terms and Conditions (T&Cs) of the DOSTs revealed a range of different factors that limited usage/accessibility or imposed liability on users. Strikingly, these T&C limitations were mainly found in DOSTs registered directly in the US, or sponsored by companies/organizations registered in the US, linked to US trade control laws, and thus restrict the services that can be made available to users in countries and territories under US sanctions. Two examples of companies that have explicitly clarified these limitations in their T&Cs are presented in table 2. It is important to note that the lack of explicit prohibition within the T&Cs of other companies does not necessarily indicate that they are available for access by researchers in US sanctioned countries. More research on the extent of geoblocking is urgently required to clarify these issues.

[Table 2]

As many other DOSTs rely on GitHub for infrastructure and hosting of resources, the T&Cs of one commercial company can have far-reaching consequences for the Open Science ecosystem. In contrast, there has been no systematic study to date examining

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whether access to the numerous preprint services hosted by COS are blocked in US-sanctioned countries. These T&Cs remain problematic as they place the responsibility on the user of the site to comply with the legislation alluded to. This raises challenges for users as they have to identify and read the relevant legislation – often in English – and access the T&Cs when they are hosted on GitHub.

US-sanctioned were explicitly mentioned in 79 of the DOSTs in the database. While many of these did not explicitly state that their services were blocked to users in countries under US sanctions, this could still be the case. Indeed, there is considerable anecdotal and documented evidence of research tools and databases being geoblocked to users in countries under sanction from the US. These could include countries such as Sudan (Bezuidenhout *et al.*, 2019), Iran, [17] Myanmar, North Korea, Venezuela, Cuba, Crimea and Zimbabwe.

Discussion

For the Open Science movement to progress and the DOST ecosystem to flourish, the evolving digital ecosystem must ensure that "*the primary outputs of publicly funded research results – publications and the research data – [are] publicly accessible in digital format with no or minimal restriction*" (OECD, 2015, p. 7). It also requires "extending the principles of openness to the whole research cycle, fostering sharing and collaboration as early as possible thus entailing a systemic change to the way science and research is done".

An effective DOST ecosystem thus has two key roles: 1) to facilitate practices that enhance open and transparent research as well as 2) to ensure that these practices –

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[17] https://github.com/pi0/github-is-blocked-in-iran (accessed 16 March 2020)

and the resultant resources - are available to researchers across the world. The analysis of the current DOST ecosystem presented above suggests that it may struggle to deliver on these roles. The unequal geographic distribution of the tools, the dominance of certain languages, cultures and entities, and the diversity of the funding models supporting the development of new tools all add complexities to the DOST ecosystem. Recognizing these power dynamics, value clashes, and infrastructural bottlenecks is essential for the future of the Open Science movement. In the section below, we discuss the results and their implications for Open Science in more detail.

Persistence and preferences

The current structure of the DOST ecosystem means that the persistence of individual tools depends on attracting a community of users and securing stable funding. This might suggest that these features support a meritocracy, whereby the "best" DOSTs persist by common consent and investment. Such a position, however, overlooks key issues such as diversity within user communities and accessibility of funding. Overlooking such issues can undermine the Open Science values described above - particularly the aspiration that the Open Science ecosystem be globally accessible and useful.

As illustrated in figure 2, many of the presented DOSTs are hosted in the United States. It is therefore likely that these tools have been piloted and beta-tested within the immediate research communities and therefore many of the design decisions integrated into the DOSTs dominantly reflect the US research environment and the preferences of the researchers in this region. Similarly, DOSTs created by commercial companies, or designed with commercialization in mind, will likely reflect the most immediate user community, namely North-American and European researchers.

While these biases could be eliminated by subsequent user-community feedback, this is not always feasible. Limited funds for long-term responsive design, and slow roll-out beyond the US and other High-Income Countries (HICs) along with the unequal distribution of researchers around the world can mean user communities develop around DOSTs before they have had any meaningful engagement from researchers working outside of these "geographical epicentres". For example, in 2013 the Europe Union (11.4% of the global population) hosted 31% of the world's researchers.[18]

This can mean that voices from other research communities can easily be overlooked - including non-English speaking countries or Low and Middle Income Countries (LMICs) with small research communities. These different research communities have to date played a marginal role in the evolution of the DOST ecosystem due to the low level of involvement in elucidation and design of tools and infrastructure. If DOSTs are designed with a specific research community in mind and tested in the same community, it can mean that the design of the DOSTs "closes" before these marginal research communities are able to engage with them (Bijker, Hughes and Pinch, 2012). This "technological closure" means that the DOSTs available for use by marginal research communities will already have a fixed design and dedicated user community. Fundamental design decisions are unlikely to alter once the DOST has become operational in the original user community. Consequently, certain tools may be integrated into the DOST ecosystem that do not suit use in non-HIC research contexts. As a result, it is possible that certain communities get "locked-in" to the use of these

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[18] The Big Five (China, European Union, Japan, Russian Federation and USA) still account for 72% of researchers worldwide but the share of China has progressed considerably since 2009, to the detriment of Japan, the Russian Federation and the USA. The share of the European Union (7.1% of the global population) has remained stable, at 22.2% in 2013, compared to 22.5% in 2009. Europe as a whole (11.4% of the global population) hosts 31% of the world's researchers. https://en.unesco.org/node/252277 (accessed 17 March 2020)

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DOSTs without having the opportunity to feed back into design decisions (Arthur, 1989; Leonelli, 2017).

Situations of "locking" research communities into certain DOSTs and digital workflows can cause the ecosystem to unintentionally perpetuate marginalizations. The design and persistence of the DOSTs not only influence the "pathways" that the research follows through the ecosystem, but also the research methods, data collection and curation methods and analysis tools used. The selection of certain tools over others can thus have far-reaching implications. The decisions incorporated into its design reflect a specific geographic context and value system can influence research practices across the globe.

Such concerns relate to the "Juan Valdez problem" discussed by Busch and Juska, (Busch and Juska, 1997) in relation to agricultural systems and technologies. Juan Valdez, a South American coffee farmer, is born into a world in which his choices are limited. Many of these limitations relate to the environment he lives in, and which he accepts as default. On the other hand, certain choices may be deliberately denied to him. "The coffee company may have a local monopoly over purchasing the beans. The state may not have invested in adequate physical infrastructure for the area, thereby making transportation costs high" (Busch and Juska, 1997, p. 696). Thus, what is possible for Juan is dictated by human and non-human relationships alike. Similarly for Open Science tools, what is possible for marginal research communities may be determined less by their preferences than by decisions made between human partners in geographically remote locations.

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It becomes apparent that more research is urgently needed. Qualitative research on the development of DOSTs would shed light on how potential design biases are addressed during the design of these tools. More information on the (lack of) diversity within user communities would highlight issues of "lock in", while engagement with LIMC researchers about the use of existing DOSTs would provide further information on the usability of these tools in non-HIC research settings.

Power brokers in the DOST ecosystem

From figure 4 above it is evident that the DOST ecosystem is dominated not only by certain countries, but also by certain companies, organizations and institutions. Such clustering - in light of funding, access to target audiences, permissive legislation and business cultures - is not particularly surprising. Indeed, it may be said to follow other models of technical expansion throughout history. Accepting this expansion as entirely normal from the user perspective, however, does not make it unproblematic.

The DOST ecosystem and the DOSTs themselves are intended to be distributed and multiplicitous to allow the maximal flexibility of research practices. Allowing a small number of entities to dominate the ecosystem and its evolution thus presents challenges to these aims. In particular, two key concerns arise: first, the dominance of certain entities causes centralization and interdependence on individual actors. Second, the dominance of certain entities allows specific approaches to Open Science, and related values, practices and preferences to be prioritized. This can affect the heterogeneity of the Open Science movement and foster a perception that there is consensus on how Open Science "should be done" (Fecher and Friesike, 2014).

In recognizing the former, the DOST ecosystem must confront a paradox. While interconnectedness is vital for fostering open, global research and removing national, disciplinary, and linguistic siloes, the same tools that facilitate this connectedness can lead to a centralism that drives out regional and local expertise and diversity. In particular, having tools such as GitHub dominate various stages of the research lifecycle in a number of tools not only enhances interoperability, but also centralization and dependence, thereby diminishing accessibility to some.

The latter concern relates to an often-overlooked aspect of technology: The intentions, experiences, priorities and cultures of the IT-professionals influence the design and deployment of the technology (Winner, 1986). All DOSTs are created against a backdrop of social values, and designed with specific interpretations of Open Science in mind. This can lead to considerable heterogeneity in what is foregrounded, prioritized and included in the design of the DOSTs. As a result, DOSTs, like other technologies, are at once both the sites and objects of politics (Jasanoff and Kim, 2009, p. 126), and foreground certain views of openness through their positioning in the DOST ecosystem.

GitHub, for example, is a commercial company based in the US. The design of GitHub, and its operating practices thus align to a specific set of values. As a result of its dominance within the DOST ecosystem, its position on key issues such as inclusion, sharing and transparency are increasingly becoming the "norm" for many users despite its political constraints and accessibility restrictions for many researchers. Recognizing such issues highlights the need for closer scrutiny of the value structures of the tools within the DOST ecosystem. Asking questions such as why tools were created, how users were recruited and why they favour one tool over another will shed light on these issues. In particular, it will highlight the limitations of allowing certain countries, tools and organizations to dominate the DOST ecosystem.

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Access and underlying infrastructures

The decisions influencing the design of DOSTs do not only reflect user community preferences and perspectives of Open Science, but also assumptions about the availability of infrastructures and resources. These include a wide range of different issues, including access to funding and the ability to make online payments, linguistic competence, access to software and hardware, as well as infrastructure availability relating to internet connectivity and bandwidth.

For many DOSTs developed in Europe or the US there is an emphasis on the tools being cloud-based. On the one hand, such an emphasis makes sense in many ways such as the ease of having nothing to install, being able to deliver the latest version of software via the browser and having access to the content from any device anywhere in the world, as long as it is connected to the internet. On the other hand, some institutions especially in the European Union prefer the tools to operate on their own servers to keep them confidential from potential competitors for patenting and to ensure data and content ownership through territorial storage. For research communities in LMICs these same design decisions form a usage barrier because of low bandwidth and intermittent internet connection that make an over-reliance on "online only" tools problematic (Bezuidenhout *et al.*, 2016).

While multiplicity in the DOST landscape can allow marginal researchers to plot alternative pathways through the OS ecosystem, this can mean that they must resort to using less popular tools. As a result, there is a chance that these researchers continue to be excluded from the user communities that are driving research forward. This has

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obvious implications for collaborations, visibility/engagement with researcher communities and perceptions of worth.

Designing DOSTs for infrastructure present in the dominant geographical regions (such as the US) legitimizes a specific expectation of service access and provision. In this way, the DOST ecosystem fails to address the recognized imbalance between central and marginalized countries and research communities. Indeed, the cost for internet access and [institutional as well as private] connectivity varies drastically across world regions and tends to be extraordinarily high in LMICs.[19] By perpetuating a set of embedded assumptions like web interfaces or connectivity, Open Science continues to perpetuate a limited perspective for "inclusion" that often falls short of being inclusive. Ensuring more inclusive design structures and processes will require ethnically and regionally diverse teams of DOST designers to ensure that infrastructural challenges are considered and responses incorporated into design decisions.

Sanctions and political clout

As demonstrated in the results section, the DOST ecosystem has to contend with a range of power dynamics external to research infrastructure. Perhaps the most pernicious of these is the role that financial legislation plays in dictating access to open resources (Bezuidenhout *et al.*, 2019). This is perhaps best demonstrated by the impact that US financial sanctions have on access to DOSTs. As demonstrated by table 3, a number of DOSTs explicitly prohibit use from individuals located in countries currently under financial sanctions from the US.

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[19] https://www.visualcapitalist.com/cost-of-mobile-data-worldwide/

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The reasons for these prohibitions are complex and often relate to the financial requirements of the funding bodies. DOSTS developed by commercial companies registered in the US, or those funded by commercial companies registered in the US, are subject to US tax law that explicitly prohibits transacting with countries under sanction. As a result, the values and political positions of the US government are integrated into the Open Science landscape via a range of different tools. From the data available, it was not possible to determine whether US organizations registered as NPO 501(c)3 or receiving fiscal sponsorship would be similarly subject to restrictions. Nonetheless, the limitations elucidated in the T&Cs represented in table 3 suggest that this issue requires considerable further examination.

In addition to the explicit restrictions noted on T&Cs, users in countries under sanction from the US may be restricted access via three additional pathways. Many of the DOSTs in the database required some form of account or login (see figure 4). This implied that the location of the users is being monitored via the tool and could provide a means to deny certain users access to the services. Additionally, the DOSTs requiring some kind of payment for services - either freemium or membership fees - could restrict access from countries under sanction, as online financial transactions are largely prohibited from these countries. Third, governance of certain elements of the Open Science landscape by high-level but poorly elucidated legislation - such as cryptography software by the Wassenaer agreement[20] - can mean that providers restrict access as a means of precaution. Expanding analytical services such as AlternativeTo and Terms of Service Didn't Read[21] to DOSTs will help researchers make informed decisions as they navigate through the Open Science ecosystem.

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[20] https://www.wassenaar.org/ (accessed 17 June 2020)
[21] https://alternativeto.net/, https://tosdr.org/

This creates situations of marginalization and lack of access for certain communities of end-users. Even more concerning, however, is that one country's political preferences are able to dictate the evolution of aspects of the DOST ecosystem. While it is important to note that the introduction of these political values is likely done unintentionally or via funding-related necessity, the impact is nonetheless severe. Acknowledging that certain aspects of the DOST ecosystem are unavailable to certain communities of users is vital for further critical reflection on the evolution of Open Science. In particular, what does this mean for the core values of the Open Science movement and the notion of a "digital commons" (Hess and Ostrom, 2007; Bezuidenhout, 2020)?

A critical appraisal of the DOST ecosystem

The results and discussion presented in this paper draw attention to problems within the current DOST ecosystem. Without detracting from the importance of the emergence of more and more discipline- and region-specific DOSTs, and the work of dedicated individuals who create them, words of caution are appropriate. The results of this paper demonstrate the heterogeneity of the actors, power dynamics and stakeholders that are currently driving and dominating the evolution of the DOST ecosystem. Even if all DOSTs were created by well-meaning individuals who wish to promote Open Science, one cannot simply assume that the resultant ecosystem will automatically reflect and perpetuate the core values of Open Science. Instead, a range of different factors inherent within DOST design create a landscape that continues to perpetuate marginalization and exclusion.

This marginalization is multifaceted. Not only are marginal research communities excluded from design decisions of DOSTs, they are likely also sidelined in the user communities that develop around them. Moreover, DOST (un)availability/accessibility does more than exclude researchers from sharing communities, it also dictates

research practices and digital workflows. In this way, the design of the DOST ecosystem can affect both present and future research. While the DOST ecosystem is dynamic and multiplicitous, the dominance of a few entities is rapidly driving forward a "status quo" of how research should be done. Once such practices reach a "carrying capacity" within the global research community, they are unlikely to be easily adapted. This can mean that the current design of the DOST ecosystem marginalizes future, as well as present, researchers.

The results and discussion in this paper point towards the need for a new model to critically evaluate the evolving DOST ecosystem. In particular, it highlights the need for more active inclusion of diverse user communities in all stages of DOST development and deployment.[22] This will make the embedded politics of the DOSTs ecosystem more transparent. Conversely, there is an imperative to identify examples of DOSTs developed in, for and by researchers in Africa, Asia and Latin America which can serve as examples of alternative design practices. This will provide a better understanding of how diversity can be better supported in the DOST ecosystem. This will allow critical reflection on the politics that are not visible in centrally-located tools that are being made explicit in the non-central ones.

Many of the issues mentioned and concerns raised in this paper will not come as a surprise to Open Science practitioners. Nor will it be surprising to add that the current model of persistent barriers continues to place certain members of the Open Science community in uncomfortable and sometimes unethical positions. These include having the choice of Open Science tool dictated to them through lack of engagement in community consensus or due to feasibility in a local context with digital infrastructure deficiencies. It also includes having to operate in an ecosystem that regularly requires

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[22] Key resources such as the Open Science Grassroots Community Networks listing by CoS will provide valuable further evidence for inclusion https://twitter.com/Gen_R_/status/1146069028546523136?s=20

the decision making between non-participation or breaking law by consulting scholarly pirate software.

Allowing such situations to persist undermines the aims of the Open Science movement. Recognizing this places a responsibility on the global Open Science community members to make discerning decisions about the tools that they use. This requires that the T&Cs of DOSTs, their funding structures and their infrastructural constituencies are all closely scrutinized before new tools become embedded in the DOST ecosystem. Similarly, funders, research institutions and other stakeholders need to critically assess the impact of introducing DOSTs to the ecosystem, and advocating their use amongst their researchers (ie. through the [San Francisco Declaration on Research Assessment](#)).

The section above highlighted how inequalities, marginalization and injustices were perpetrated by the current structure of the DOST ecosystem. The design of DOSTs, the ways in which they are interlinked, and the dependencies/dominances of certain entities raises the question of whether the DOST ecosystem can realise the aspiration of becoming a truly "unlimited digital commons" in its current structure. From the data presented above, it would seem that things need to change.

Nonetheless, the DOST ecosystem is a complicated landscape, and imposing a specific value set or "way of doing things" will harm the richness and diversity of this rapidly evolving field. Rather than imposing restrictions on what should constitute a DOST, we suggest that those designers and users be supported to critically reflect on the values that they are introducing into the ecosystem. There are many models currently in use on

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how to balance well-intentioned innovation with pragmatic requirements, and these need to be more strongly developed for DOSTs.

One such model, Responsible Research and Innovation (RRI), has made considerable contributions to discourse around socially responsible innovation. Opening up access to data and support of Open Science are fundamental components of the RRI model (Stilgoe, Owen and Macnaghten, 2013). To date, little has been done to turn the RRI lens back on the Open Science movement that it evolved from to ask what an RRI model for Open Science tools could look like. Such a model needs to address questions such as how to foster a free and open "ecosystem" when the OS tools are generated by a diversity of actors - NPO, NGO, governmental, commercial, volunteer) that can hold highly divergent values while supporting Open Science. Similarly, how a free and open landscape can be created when financial and governmental regulations and requirements influence tool design needs to be looked at as well; a promising assessment is currently underway by the Invest in Open Infrastructure initiative.

It is important to note that community-determined standards for what constitutes "Open Science" already exist in a number of different areas. Within Open Access publishing, for example, both ROMEO Sherpa and the Directory of Open Access Journals (DOAJ) clearly define what is required of a publication to be Open Access. Similarly, re3data has developed a list of criteria that any open repository needs to demonstrate. Such community standards have been highly influential and are being widely adopted by research communities and provide for cross-regional and cross-disciplinary agreement and functionality. While conversations about Open Science tool standards have existed for more than a decade, the broader community needs to be engaged for such standards to become a reality.

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The design of the DOST ecosystem not only determines how research is conducted today, but also determines the directions and practices of future research. Allowing certain actors, pathways or regions to become too entrenched will allow inequality and marginalizations to persist and become a future norm. Research practices are changing rapidly (ie. AI, big data), international politics are in flux (ie. Brexit, COVID-19 pandemic) and historically marginalized research communities (ie. citizen scientists and LMIC researchers) are increasingly vocal and influential (Aspesi and Brand, 2020). It is now the right time to critically assess what has already been built, and what the united global research community wants to take forward into the future.

Concluding Comments

Much of the OS ecosystem has been developed by volunteers, who donate time and expertise to developing DOSTs, infrastructures and interoperable practices. This community has the history, expertise and perspectives to take up the challenges raised in this paper. How, they need to ask, can they guide and adapt the ecosystem that is rapidly changing research? This requires a reframing of Open Science responsibilities, from contributing labour and data to discussing the complex power dynamics underpinning the evolving ecosystem. Only then will the UNESCO theme 2019 of "Open Science: leaving no one behind" become a reality.

The OS landscape is ever increasing globally, also in historically underrepresented regions such as Latin America, Africa and Asia. We therefore suggest to tie the digital development and regional adaptation of DOSTs on the Open Science Manifesto, Towards an Inclusive Open Science for Social and Environmental Well-being - https://ocsdnet.org/manifesto/open-science-manifesto/. In particular for the more dominant digital tools for open research and communities in Europe and North America,

there is a dire need for more active consultation and inclusion of research stakeholders from various parts of the world in order to successfully design a truly global Open Science community, culture and infrastructure (Albornoz *et al.*, 2018).[23] Moreover, key expertise from development networks, such as ICT4Dev and Tech4Dev (Hostettler, Besson and Bolay, 2018) can play an important part in developing a more equitable Open Science ecosystem.

For the moment, however, building a body of evidence detailing DOSTs, their uses and the communities they use them is vital. Only through gathering this evidence can strategic and informed decisions about future ecosystem investments be made inclusively.

Figure Legends

Figure 1. A) Diagram from Bosman and Kramer (2016)[24] demonstrating diversity of DOSTs, linkages between tools at different stages of workflow. Green line demonstrates a potential research workflow involving DOSTs. Image shared under CC-BY license. B) Pictogram of a random digital tool representing the tools displayed in 1A with influencing aspects addressed in this paper: underlying values, financial models, language choices, geographical location, user communities.

Figure 2. Visual map using the software Kumu.io. A) Clustering overview of all tools sorted by workflow step (url: https://kumu.io/a2p/dost#dataset/workflow-step); B) Clustering overview by geographical location of the tool or the respective host institution (url: https://kumu.io/a2p/dost#dataset/workflow-step); C) Clustering overview by host

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[23] https://en.unesco.org/science-sustainable-future/open-science
[24] https://101innovations.wordpress.com/workflows/ (accessed 10 August 2020)

institution for the tool (url: https://kumu.io/a2p/dost#dataset/host); D) Focus view on hist self-hosted tools – closeup from square in C).

Figure 3: Number of tools per host location. Regions displayed are the United States of America (US), the European Union (EU), the United Kingdom (UK) and other parts of the world with concentration on US territory. *'Other'* includes Argentina (n=1), Australia (n=2), Brazil (n=1), Canada (n=7), Colombia (n=1), Mexico (n=1), South Africa (n=1), Switzerland (n=5), with a total of n=242.

Figure 4: Illustration of the funding models of DOSTs. The funding sources for the respective tools were classified as a) Commercial (n=56, 23.1%); b) Grant (n=19, 7.9%); c) mixed (commercial and grant, n=122, 50.4%), and d) Institutional (n=44, 18.2%). 0.4% of the tools (n=1) had no funding source specified. n=242.

Figure 5: Tool providers across workflow showing the number of tools per workflow step.

Tables

Table 1: Key pressures on the DOST ecosystem

Attributes	Elements	Impact on OS ecosystem
Objectives driving tool creation	Business models, investment, venture capital, grants, philanthropy, profit, community activities	Influence on design decisions Longevity
Recruitment of user community marketing	Word of mouth, advertising, sponsorship, mandated by funder, institution, government, disciplinary community	Evolution of user community Prioritisation of tool over competitors, alternatives

Integration with other tools	Intentional design to connect with specified tools, widespread adoption into other tool designs, community-evolved connections	Interoperability
Host	Host organization, host country	Requirements and expectations of host, political constituency, interruption through economic sanctions
Regulations and legislation	Location-specific legislation, selection of regulation, oversight of activities	Financial legislation Oversight and mandated practice Selection of other codes, regulations, requirements
Materialities and infrastructures	Reliance on underlying digital landscape and information and communication technologies	Integration into digital landscape Financial/technical resources required to effectively use tool
Systems of thought	Social and political values, rationales	Endorsement and influence by capitalism, democracy, egalitarianism, socialism
Specified practice	Data formats, language, software systems	Need for data standards, file formats, user language, etc

Table 2: Example T&Cs of two entities within the OS ecosystem

DOST	Statement in T&Cs	Notes

GitHub	You may not use GitHub in violation of export control or sanctions laws of the United States or any other applicable jurisdiction. You may not use GitHub if you are or are working on behalf of a Specially Designated National (SDN) or a person subject to similar blocking or denied party prohibitions administered by a U.S. government agency. GitHub may allow persons in certain sanctioned countries or territories to access certain GitHub services pursuant to U.S. government authorizations. […] To comply with U.S. trade control laws, GitHub recently made some required changes to the way we conduct our services. As U.S. trade controls laws evolve, we will continue to work with U.S. regulators about the extent to which we can offer free code collaboration services to developers in sanctioned markets. We believe that offering those free services supports U.S. foreign policy of encouraging the free flow of information and free speech in those markets.[25]	The countries affected are Crimea, Cuba, Iran, North Korea, and Syria. There have been reports of access to GitHub being blocked in these countries.
Center for Open Science	The COS is based in the United States. The COS makes no claims that the data or content on its Websites or Services is appropriate or may be downloaded outside of the United States. Access to the Websites and Services may not be legal by certain persons or in certain countries… . You may not use the Websites or Services to violate any applicable local, state, national, or international law, including without limitation any	The T&Cs for the COS are hosted on GitHub, which makes access to the T&Cs from US-sanctioned countries difficult .

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[25] https://help.github.com/en/github/site-policy/github-and-trade-controls (accessed 16/03/2020)

	applicable laws relating to antitrust or other illegal trade or business practices, federal and state securities laws, regulations promulgated by the U.S. Securities and Exchange Commission, any rules of any national or other securities exchange, and any U.S. laws, rules, and regulations governing the export and re-export of commodities or technical data.[26]	

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[26] https://github.com/CenterForOpenScience/cos.io/pull/1025/files (accessed 16 March 2020)

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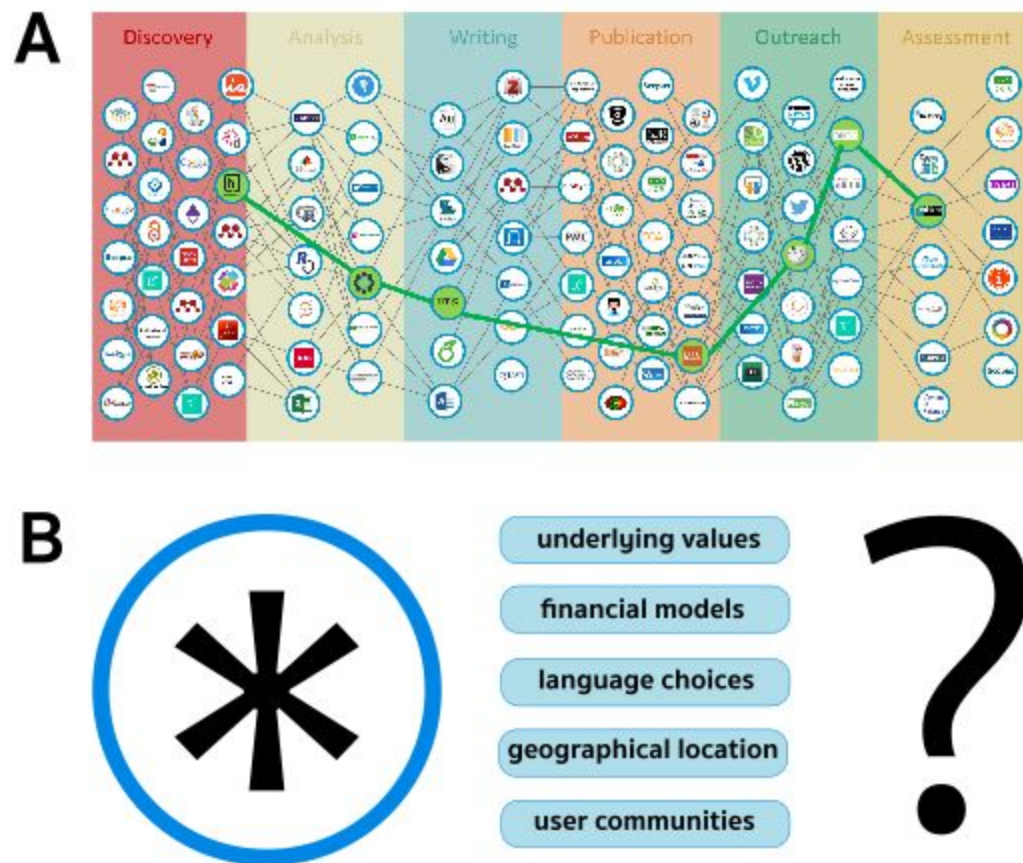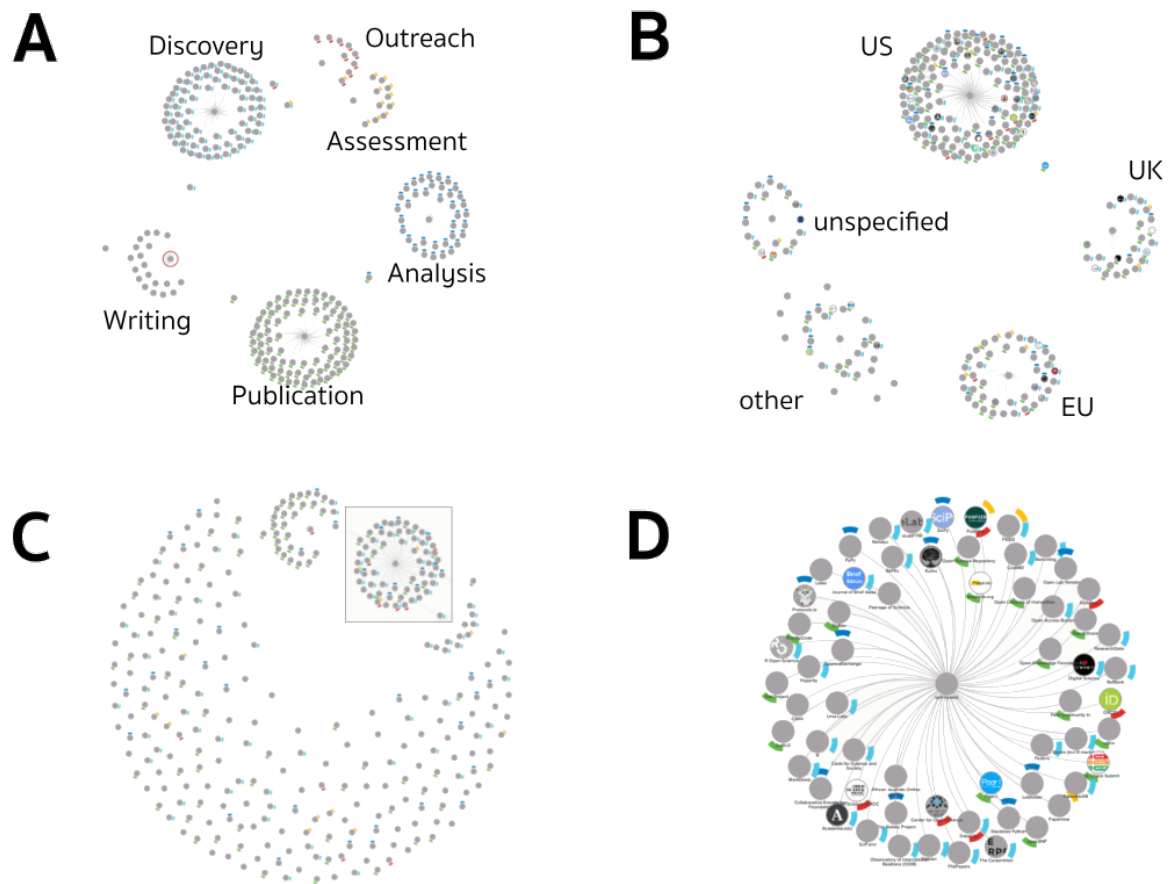
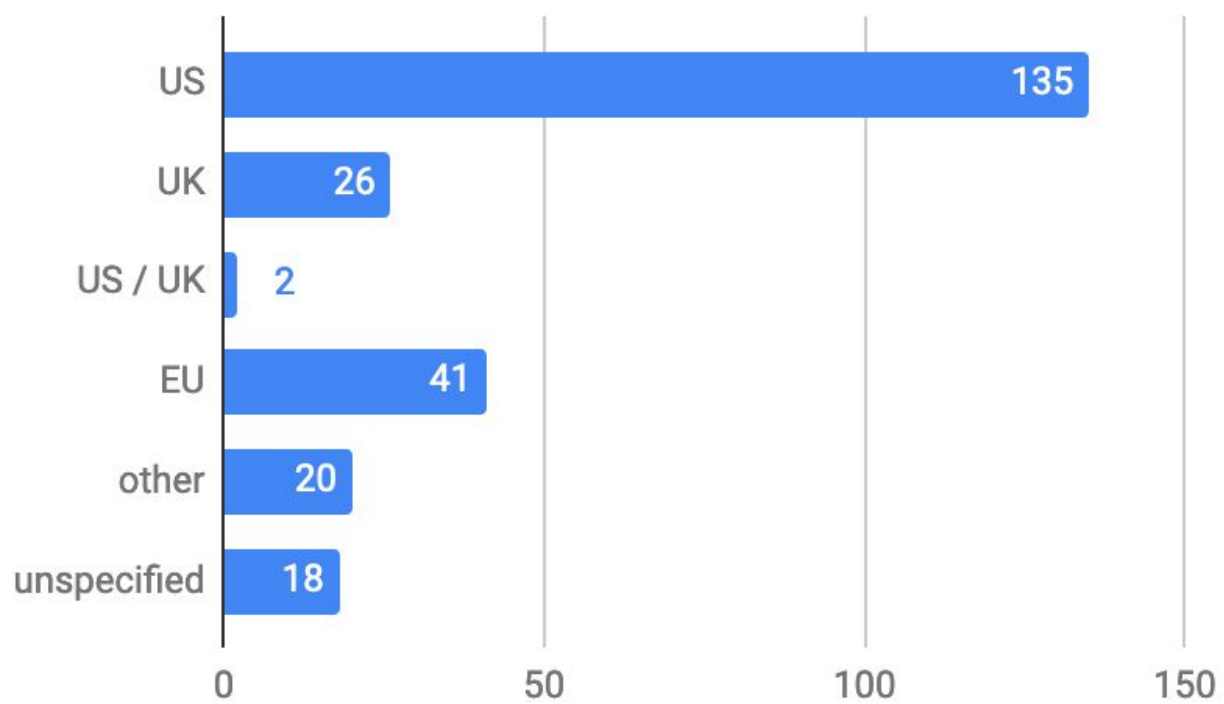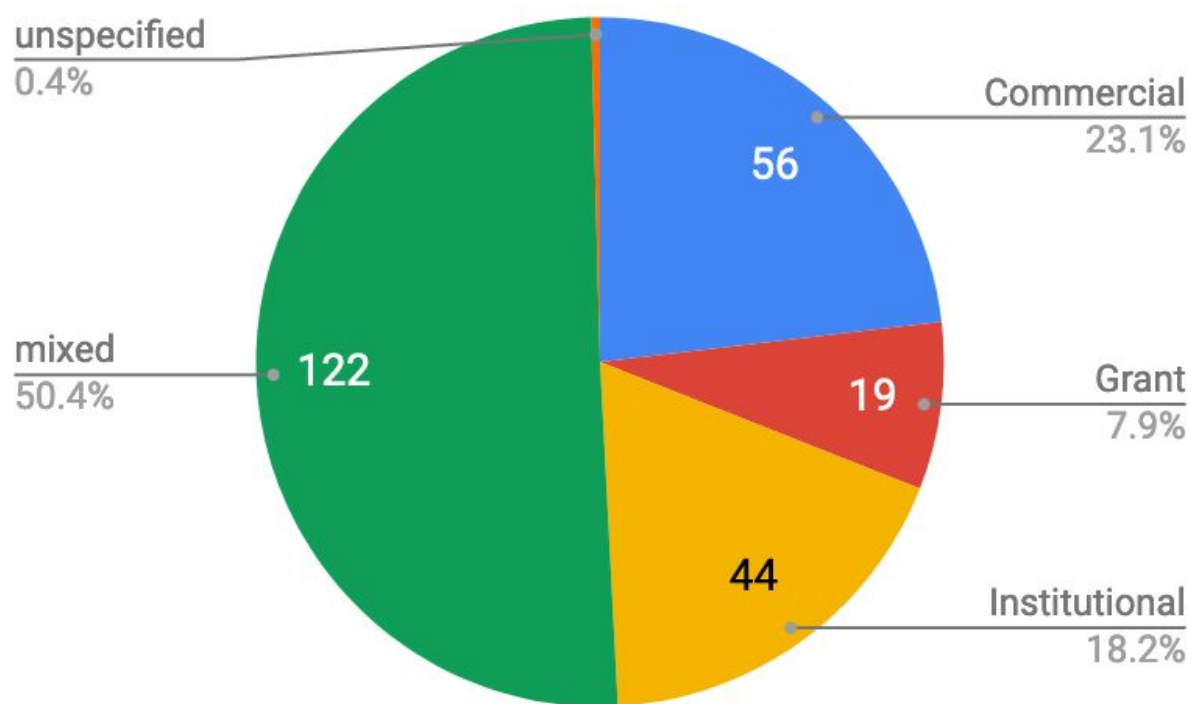# Figures

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

	Discovery	Analysis	Writing	Publication	Outreach	Assessment
GitHub	19	14	4	11	1	2
Center for Open Science	2	2		26	1	
DigitalScience	9		2	1		
Elsevier	2	1	1	1		4
Wikimedia	5	1	3	2		
OurResearch	2			1	1	1
ScienceOpen	2			1		
Public Knowledge Project	1			3		