Preprints & Pandemics: Interventions into the Dynamic System of Scholarly Communication

Micah Altman, MIT; Philip N. Cohen, University of Maryland; Jessica Polka, ASAPbio

(Authors are listed in alphabetical order. Contributions are described in detail in the Acknowledgements sections.)

1 ABSTRACT

The COVID-19 pandemic illustrates how scholarly communication can respond to external shocks, even as the ecosystem is evolving rapidly. Many argue that swift and fundamental interventions in the system of scholarly communication are needed; however, it is much easier to identify changes in scholarly publications than to characterize emerging interventions in the processes and institutions of scholarly communications -- and harder still to understand the impact of interventions. This is illustrated by comparing the approaches applied by the scientific community to understand public health interventions with those applied by the scholarly communications community. There are substantial disagreements over the short- and long- term benefits of most proposed approaches to changing the practice of science communication, and the lack of systematic, empirically based research in this area makes these controversies difficult to resolve. We argue that experience within public health can be usefully applied to the science-of-science. Starting with the history of DDT application, we illustrate four ways complex human systems threaten reliable predictions and blunt ad-hoc interventions. We then show how these apply to a previous intervention in scholarly publication -- open access based on the article processing charge (APC) -- to yield surprising results. Finally, we outline how these problems may affect assessment of the rise of preprints, and we identify four mechanisms that can be adopted from public health to mitigate these threats.

2 INTRODUCTION

In the first year of the pandemic, researchers and health authorities learned progressively more about all aspects of the disease. This included the determinants of viral contagion, disease progression and severity, the risks to physiologically and sociologically vulnerable vulnerable populations, infection control protocols, and social interventions to reduce spread. Although many faulted the World Health Organization (WHO) and major governments for being slow to implement adequate public health measures, these scientific developments occurred at unprecedented speed [1]. In contrast, our understanding of how scientific research and communication changed during the same period lags behind.

Progress in understanding and mitigating COVID-19 built on a scientific and empirical foundation that describes the dynamics of global health at the systems level; standards, processes, and infrastructure to measure and compare outcomes; an evidence base that supports comparisons across time and between groups; and methodology for conducting and analyzing interventions that support statistically reliable inferences about their local and systems effects. The system of scholarly communication – which plays a vital role in public health and all other scientific fields – currently lacks these features.

The scholarly ecosystem is evolving rapidly, and many argue that fundamental changes are needed. A wide spectrum of government agencies, scholars, and corporate entrepreneurs (among many others) have proposed changes to practically every part of the system. These include proposals to change the way that research is funded and research outputs evaluated [2]; how researchers are trained and credited [3]; how research is planned and designed [4]; how evidence is collected, managed, and shared [5]; and how research findings are published, cited, and replicated [6]. In this context, the COVID-19 pandemic put enormous pressure on the system of scholarly communication in science in particular. The urgent demand for timely science led to an increased role for preprints, for example, as scientists sought to push their research forward more rapidly [7], and to a dramatic increase in media and public attention to preprints [8]. As with any large-scale perturbation of a dynamic system, however, we will argue that the results of this change are complex and challenging to derive.

In this paper, we explore the need to increase the capacity for scientific communication to improve by systematically assessing itself. We describe how a systems approach can help identify and anticipate the consequences of changes to scholarly communication, using two examples: the article-processing charge model and preprints. We suggest greater efforts to anticipate categories of potential consequences, and to design assessments with the range of effects in mind. In so doing, those who would introduce interventions into the system may increase both the chance that they succeed and their capacity to learn whether and how they have.

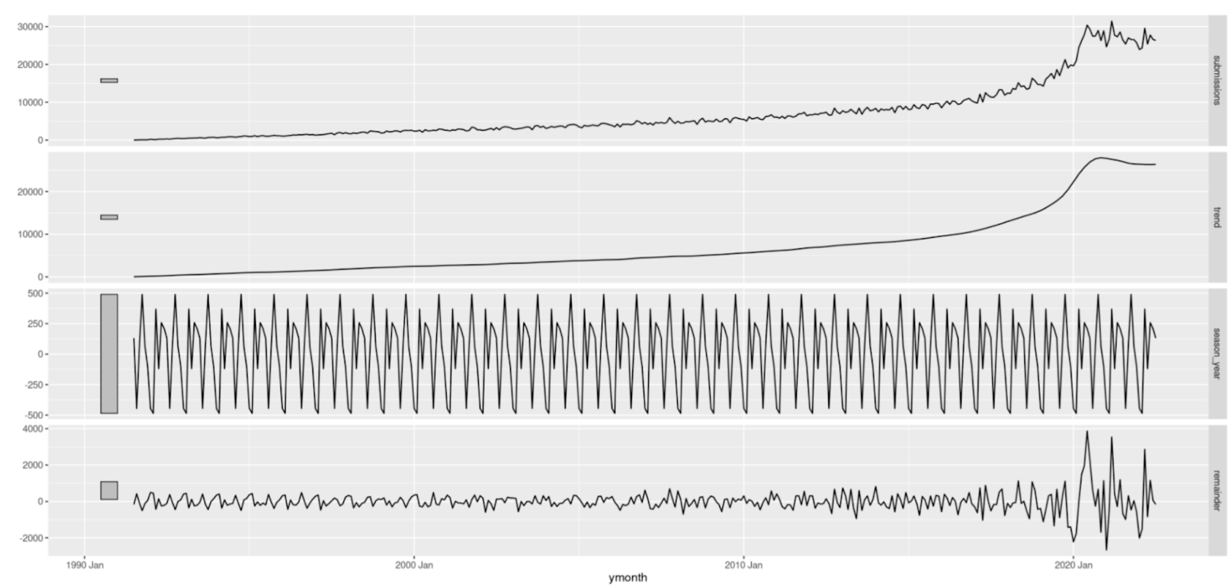
We focus on the use of preprints in the context of the COVID-19 pandemic specifically, and its attendant controversy, because the growth of preprints implies a major change in how scientific scholarly communication works. The use of preprints to disseminate research findings is a practice commonly dated to the founding of arXiv in 1991 [9]. Their use was increasing exponentially before the pandemic, and in 2021 there were approximately 360,000 preprints posted, across arXiv, bioRxiv, medRxiv, OSF Preprints, PsyArXiv, SocArXiv, and additional services indexed by Europe PMC – an increase of 70% from the number posted in 2019. For comparison, relative to the number of articles listed in Web of Science, preprints rose from 10% in 2019 to 13% in 2021, with 2020 representing the greatest one-year increase since 2013.[1]

In comparison, another large intervention, the article processing charge (APC) model of open access publishing – to which we will return below – represents a larger share of scholarly publishing, having reached 26% of articles in Journal Citation Reports journals by 2019 [10]. Elsevier reports that 20% of its

[1] For these counts we add arXiv submissions from https://arxiv.org/stats/monthly_submissions and biorxiv.org (search results) to other preprints listed by Europe PMC at https://europepmc.org/Preprints. The Web of Science count reflects all articles listed for each year.

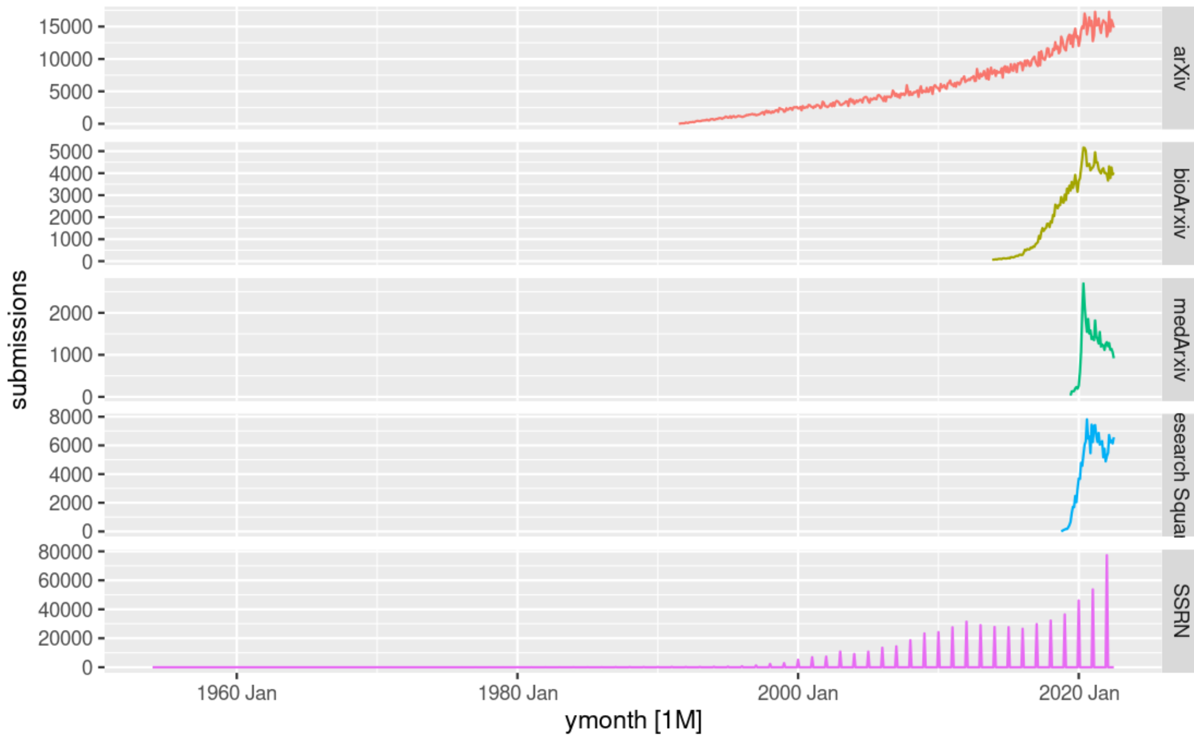
articles published in 2021 were covered by APCs, an increase from 14% the previous year [11]. Clearly, preprints and APCs -- both rapidly growing innovations in the development of scholarly communication -- comprise a substantial portion of scientific and other scholarly output, with the former representing a more dramatic increase during the COVID-19 pandemic.[2]

However, the exponential nature of the preprints trend cannot be taken for granted as a permanent feature of the scholarly communication landscape. As Figure 1 shows, there was a large number of papers posted in March-May 2020, followed by an unprecedented decline in the rate of increase. This change is most dramatic in the data for bioRxiv and medRxiv (panel B), but is apparent in the combined data as well (panel A). Seeing a change such as this prompts questions about the extent to which current changes reflect a change in cyclicity, a one time increase, or an acceleration of production. Furthermore, did the pandemic prompt changes in the composition of research outputs, and types of researchers participating in publication? Moreover, these descriptive questions are naturally accompanied with causal questions: Why did these changes in the production of preprints occur? Without an evidentiary base from which to study and compare these descriptive trends, the relationship between dramatic shocks such as the pandemic and ongoing changes such as the increasing use of preprints is difficult to analyze.



(a) Monthly Preprint Volume over Time -- Totals and Time-Series Decomposition
(Note: Excludes SSRN -- which records issue date by year only.)

[2] This brief history should not give the impression that preprints and APCs arrived suddenly to disrupt a previously-stable system of scholarly communication. In fact, the practice of journal peer review as commonly recognized today dates only to the 1970s, and thus was only a few decades old when preprints arrived on the scene [12].



(b) Preprint Volume by Source

Figure 1. Monthly total preprint issued from leading preprint servers since inception.

As with the case of preprint trends, the current evidentiary base for understanding scholarly communications and other scientific outputs in general remains incomplete. Much of our knowledge comes from individual analyses focused on specific research questions published in scholarly journals. As a result, our systemic knowledge lags years behind the data, and contains many gaps. Moreover, many analyses rely on databases such as Clarivate's Web of Science, Google Scholar, Elsevier's Scopus, and Digital Science Dimensions -- which are proprietary, use opaque methods, and are subject to undocumented revision over time. On the other hand, some open resources, such as the database of retracted scientific papers maintained by Retraction Watch – the only systematic data collection of its kind – is produced by a small nonprofit organization with a budget of less than $100,000 per year (https://retractionwatch.com/the-center-for-scientific-integrity/). There are some notable initiatives in progress to share open data on the scholarly ecosystem, and to produce standardized indicators and the volume and types of science output systematically over time, using existing open data sources [13–16]. However, most of these are still in early stages, are funded through grants and contributed efforts, and lack a sustainability model.

In contrast to scholarly communication, the evidence base for the field of public health is much more open, current, complete, systematic, and standardized. For example, public health systems run on accepted protocols for surveillance (e.g., https://www.cdc.gov/publichealthgateway/nphps/index.html), with standardized measurement, shared data, and norms of accountability [17]. One program, the

Demographic and Health Surveys (https://dhsprogram.com/) has facilitated more than 400 surveys in 90 countries, which are largely implemented to common standards and collect comparable data.

The comparison between the public health system and the scholarly communication ecosystem only goes so far, as they differ fundamentally in scope and mission. And the public health system suffers from its own structural shortcomings, involving underfunding and political conflicts, among many other issues (including dominance by private interests; for example, in 2020-21 the Gates Foundation contributed more to the World Health Organization than did any other country except Germany – 33% more than the U.S. government [https://open.who.int/2020-21/contributors/contributor]). Notwithstanding, a lesson to be extracted from this comparison is the key role that a robust and accessible infrastructure for assessment and evaluation of interventions plays in understanding and intervening in complex human systems.

3 LEARNING FROM PUBLIC HEALTH INTERVENTIONS

The history of public health is replete with cases in which selecting an intervention to pursue is difficult because the same problem may have multiple causes; in which assessing interventions is difficult because they slip within the stream of changes already underway; and in which indirect effects flowing from an intervention defeat its intended aims. We can use experiences from public health as exemplars for the syste of scholarly communication communication. Consider, for example, the use of household dichlorodiphenyltrichloroethane (DDT).

DDT application to control mosquitoes, starting in the 1940s, was initially a successful intervention to combat malaria in the affected regions of Africa, Asia, and the Americas. The treatments resulted in reductions in relevant mosquito populations and in subsequent malaria cases and deaths, with beneficial economic effects [18]. However, DDT would later emerge as a paradigmatic case of unintended consequences for public health interventions [19]. One common effect was the decimation of helpful species. For example, DDT was fatal to a parasitic wasp in Malaysia, but not to its prey, a caterpillar that fed on thatched roof material. As a result of DDT application, therefore, the local human population experienced deterioration of their houses as the caterpillar was freed from predation [20]. Another ecosystem adaptation was the spread of resistant species following the use of DDT and later generations of insecticides, leading to resurgences of mosquitoes and even malaria [21,22]. And, of course, there were the human health effects of DDT, and its effects on species up the food chain from its intended targets [23,24]. Nevertheless, because of its advantages relative to existing alternatives, DDT still has the endorsement for limited use of some public health agencies, including the WHO [25].

Some aspects of the cautionary tale of DDT for malaria control are illustrated in Figure 1. Based on successful lab results, initial use of DDT in the field focused on its short-term efficacy to produce the desired outcomes (shown in green): mosquito use and malaria reduction within targeted areas. Measuring these outcomes showed the intervention to be highly successful.

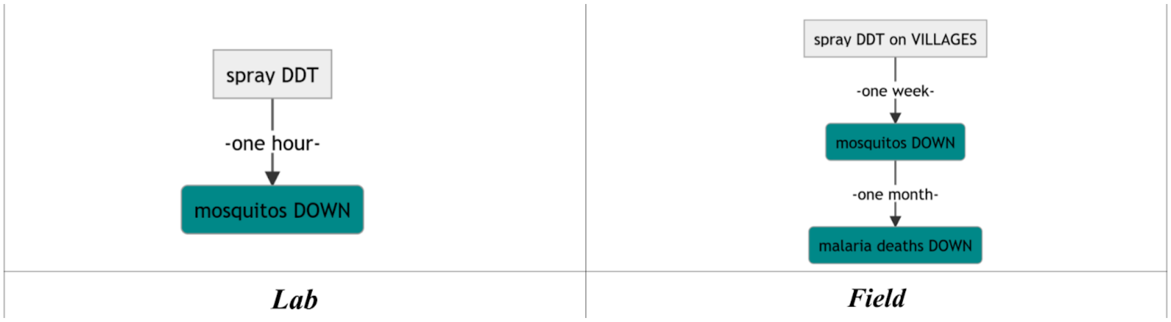


Figure 1. Measured local effects of DDT administration.

Figure 2 shows a more complete picture. Side-effects (in dotted boxes) were not systematically monitored, and contributed to a range of adverse effects (shown in pink) which emerged only later, such as the deterioration of roofs in DDT-treated areas. Years later it became apparent that DDT had stressed the entire biosphere, leading eventually both to global extinctions and to local increases in malaria, partly due to the emergence of pesticide resistant mosquitoes [24]. This example focuses on effects of the pesticide in the biological ecosystem; human interactions also complicated the effects of DDT application programs, including migration from affected areas, the lack of trained pesticide applicators, and people replastering their walls to cover up DDT stains [18].

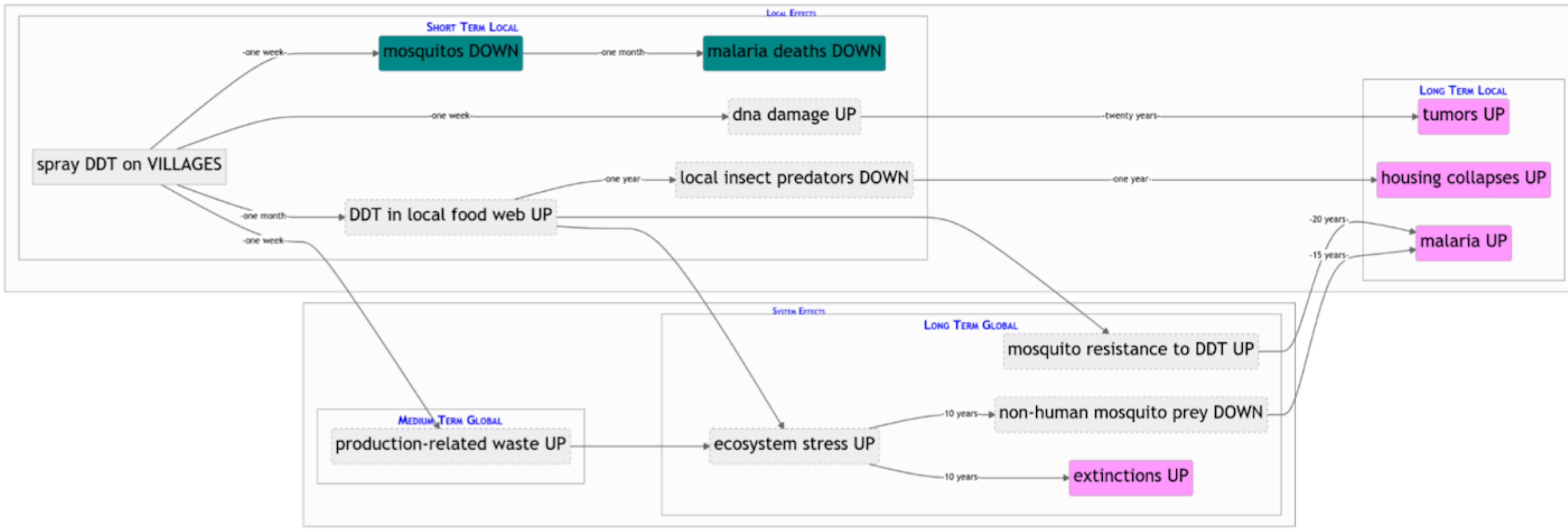


Figure 2: Measured and unmeasured effects of local DDT application.

It may have been impossible to predict the impact of DDT on the eggshells of California condors before DDT was deployed [26], but the experience of that intervention has surely helped inform the need for wider monitoring and assessment in subsequent efforts. DDT is a prototypical example, but public health interventions provide a panoply of cases in which targeted interventions produced or contributed to undetected adverse events, degradation of unmeasured characteristics of the examined outcome, systemic effects beyond the subjects treated, or long-run dynamics that were beyond the initial scope of design and assessment. Thus, for example:

- Insecticide-treated mosquito nets, also an effective means of malaria spread [27], have been widely used for fishing, with detrimental effects on local fish habitats through the capture of juvenile fish and other species [28].
- The fluoridation of public drinking water, starting in the mid-1970s, presented a shock to the U.S. dental services industry, reducing demand for private dentistry and driving many general dentists to shrink their practices or move to areas without fluoridation [29].
- The benefits of vehicle safety innovations (e.g., seatbelts), or preventive health measures (condom use, antiviral medication), might be somewhat offset by increased unhealthy behavior as people respond to altered risk profiles [30,31].
- Some abuses of trust by institutional actors, such as in the infamous Tuskegee Study (in which African American men were denied medical care for many years to study the long-term effects of syphilis) create damage beyond the immediate harms to research subjects. In this case awareness of the abuse led to reduced doctor visits by African American men [32].

These are all cases in which effects of an intervention differ from those observed or proposed in a (real or metaphorical) laboratory. This wide range of consequences to system interventions cannot all be prevented -- in fact, they are not all negative, and they are not all innocent. A key lesson to be drawn is: effecting durable and important changes in complex systems is rarely possible absent an understanding of the scope and dynamics of the ecosystem in which the change is made.

Our intention in using these public health examples is to spur consideration of innovations to anticipate potential problems and plan to assess a diverse set of intervention outcomes. We categorize these into four threats to reliable prediction, each representing a targeted outcome for intervention, and the potential for unanticipated real-world effects.

- *Unobserved events*. Unobserved events pose a set of unknown risks to inference. Assessing only proximate effects, or events intended to be affected (such as the number of people who use a service, or the market share of a product), could hide even local and short-term costs. This leaves the researcher biased towards pronouncing the success of the intervention.
- *Unmeasured characteristics*. Closely related is the problem of narrow measurement of the intended outcome. An intervention may improve a measured outcome even as it worsens unmeasured outcomes. For example, a treatment that yields a positive outcome when applied by one set of practitioners may have negative effects when applied by others.
- *System effects*. A particular intervention may displace or replace features of the wider landscape, it may create a visible model of success or failure that attracts or deters other actors, and it may alter contextual features of the system in ways that differ from common understandings. As Figure 1 illustrates, systemic effects may be temporally distant from the initial intervention.
- *Long-run dynamics*. In any of these cases, people or organizations implementing interventions are likely to have shorter-term ambitions, partly out of necessity (such as the need to generate

income, or to attract additional investment), and thus fail to assess those unintended, unmeasured, or systemic effects that take longer to emerge. In particular, over the long run, individuals and organizations learn and adapt to the treatment, modify their strategies based on preexisting or emerging incentives, and the system as a whole re-equilibrates.

The discipline of public health has long recognized such threats to inference associated with assessing interventions, resulting in systematic attempts to mitigate them (as well as analyses of the system's shortcomings [33]). We see four major mechanisms deployed in the field of public health information to address these issues: standard frameworks for measurement, data sharing infrastructure, research design and intervention approaches, and well-articulated theory describing the global health system.

1. *Standardized frameworks of measurement.* As described in Section 2, standardized measurement frameworks and protocols are used widely in public health, emerging from the historic use of surveillance data to respond to crises [34,35]. Research studies and interventions are expected to include standardized measures, including: direct outcome of treatment (e.g., 'clinical endpoints' and 'adverse outcomes'), characteristics of the sample population treated (e.g., intended and actual sample size, population frame, selection, and demographics), and characteristics of the treatment design (e.g., time-period, assignment mechanism, and treatment protocol) [36–38].
2. *Data collection & sharing infrastructure.* Public health data is systematically collected as part of program administration, through systematic surveys and related monitoring efforts. Infrastructure and policy at the local, national, and global levels supports data aggregation and sharing. This includes data sharing requirements [39–41], data repositories,[3] and surveillance and reporting programs and infrastructure [e.g., 42].
3. *Research design and intervention approaches.* Substantial public health programs are expected to include plans for standardized summative evaluation [43] in order to determine whether and how the program meets its objectives. Public health research designs further include mechanisms such as clinical trials registration,[4] meta-analysis [44], protocol deposition [45], field experiments [46], and (group-) randomized control trials [47].
4. *Systems theory.* Public health is guided by systemized theory encompassing epidemiology [48] , public health behaviors [49,50], and population demography [51], as well as a broad range of specific disease mechanisms. As a whole, theory suggests the conditions under interventions are most likely to spill over to others within the group or have externalities outside of it, where critical parts of the system affect each other; and how patterns of unwanted dynamics (e.g., adaptive behavior) could arise.

---

[3] Data sharing infrastructure in health and medicine is extensive, including summary indicators databanks (such as provided by the World Bank (<https://data.worldbank.org/indicator>), OECD (<https://stats.oecd.org/>) , and World Health Organization global health observatory), official statistics (such as the National Vital Statistics System https://www.cdc.gov/nchs/nvss/index.htm) , and open repositories for sharing research data (see. for example the catalog maintained by the national library of meicine <https://www.nlm.nih.gov/NIHbmic/domain_specific_repositories.html>).

[4] The guiding document on the research ethics, the revised *Declaration of Helsinki* < *https://www.wma.net/policies-post/wma-declaration-of-helsinki-ethical-principles-for-medical-research-involving-human-subjects/*> *,* require trial registration, as do most major funders (e.g. registration is one of the 10 EViR guiding principles: < https://evir.org/our-principles/ >) , and most medical journals (per the ICMJE requirements <https://www.icmje.org/recommendations/browse/publishing-and-editorial-issues/clinical-trial-registration.html>) .

In summary, standardization reduces the risk of unwanted effects going undetected, and supports generalization. Data infrastructure enables observation beyond the local- and short- term effects, including system dynamics. Research designs support the community as a whole in accumulating reliable evidence across studies, and linking programs with larger patterns of outcomes. And, although theory may not be not precise enough to predict or avoid all adverse dynamics, it aids in their identification, guides development of monitoring systems, and is improved through empirical tests.

In contrast to this suite of mechanisms, we are only starting to recognize the dynamics of the scholarly knowledge production system. Theory and research describing the scholarly ecosystem are insufficiently well-articulated to generate testable predictions about the generalizable effects of standardized interventions within local communities of practice. Further, the absence standard measurement, comprehensive data collection and sharing infrastructure, and causal research design makes building systematic theories challenging. This scarcity weakens the ability to identify and prevent adverse system dynamics that pose the most risk to long term interventions.

4 INTERVENTIONS IN THE SCHOLARLY ECOSYSTEM

4.1 Previous Interventions: APCs

The scholarly communication ecosystem is a complex human system, and interventions may result in the phenomena we describe above. This is illustrated by the consequences that emerged from a previous major intervention in science publishing: Open access publishing paid for with article processing charges (APCs), the model popularized by the PLOS megajournals beginning in 2003. Early proponents of open access publishing were convinced that scientific journals should not charge readers to access their articles, but left open the means by which publishing expenses would be covered [52]. In the implementation, the first PLOS journal (*PLOS Biology*) charged an APC of $1500, which was intended to be "less than 1 percent of the cost of conducting the research itself" [53]. Despite initial concerns that commercial publishers would stand in the way of open access publishing [54], APC-based open access rapidly gained market share among both nonprofit and for-profit publishers, with payments increasingly being bundled into large contracts between universities or research funders and publishers [55]. Consistent with the original intent of the initiative, this business model appears to have increased the share of research reports that are free to read online. However, once the model was accepted it became possible (some would say necessary) for APCs to rise. Whether justified by costs or not, an inequality emerged in which high-prestige journals (including hybrid journals that charge to unlock individual articles) demand higher APCs, contributing to disparities in author access to top-tier publications [56,57]. And an industry of low-quality publishers has adopted the business model as well, extracting profits from poorer institutions and authors [58]. Figure 3 illustrates selected spillover effects of this launch, using the same causal graph notation as above.

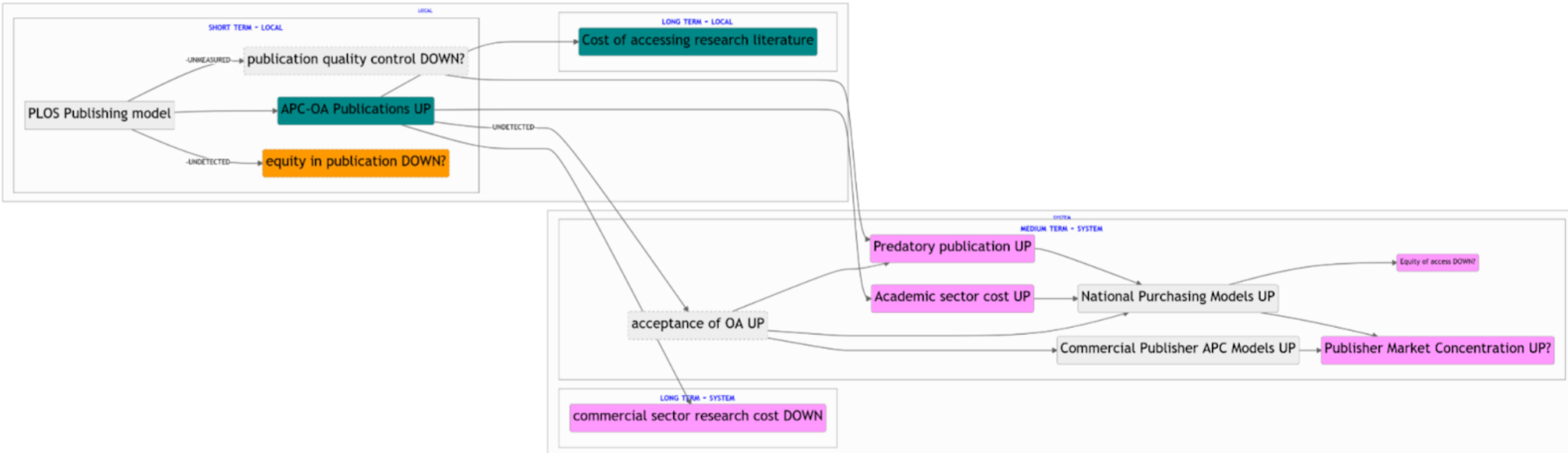


Figure 3: Some Unexpected Effects of Articles Processing Charges

As illustrated in the figure, the introduction of APC's had unanticipated consequences along the lines described above:

- *Unobserved events*. PLOS's success initially was evaluated primarily through the measurement of papers submitted and published. This is a natural target, but leaves the choice not to submit unobserved. This blind spot underlies concerns that the APC model could deter scientists with less resources (particularly in the global south) from publishing independent of the research's scientific merit [59]. This threat to equity in science is further exacerbated by incomplete measures, as the diversity of authors (and potential authors) is not systematically assessed.
- *Unmeasured characteristics*. Access and publication charges are generally public, and time to review is relatively easy to measure, but the quality of review is difficult to measure. Further, PLOS and similar journals combined the use of APCs with qualitative changes to the review process that prioritize technical correctness over novelty or impact. This dynamic can lead to "quality censoring," decreasing the ability to measure quality through publication [60].
- *System effects*. As the APC model becomes increasingly popular, a substantial portion of the systemic cost of publishing is shifted from the reader to the author (or their sponsoring organization). Part of this is intended, shifting costs away from the under-resourced general public readership onto the funded research sector. However, the adoption of the APC model also has the unintended result of shifting costs within the research sector -- in particular from commercial research organizations (some of which are well-funded) and less-research intensive academic institutions to research-intensive universities [61,62]. Further, this shift in costs affects long-run dynamics by creating incentives for large research organizations or consortia to bargain for collective APC licensing [63].
- *Long-run dynamics*. It is possible that the increasing adoption of APC publishing, in a regime in which the quality of peer review is difficult to discern, made predatory publishing models profitable [64]. In parallel, the commercial publishers adapted to the acceptance of APCs by developing a variety of APC publishing models, especially with hybrid OA journals. By mid-decade, commercial publishers succeeded in capturing the majority of revenue generated by the APC publishing model [65], even as scholarly publishing has continued its trend of corporate consolidation. In the long run, comprehensive licensing agreements between large research organizations and commercial publishers -- which lower the costs to both read and publish for those covered -- raise further equity concerns for independent researchers, those at poorer institutions, and those in the global south. [66,67]

4.2 Recent interventions: Preprints

By some interpretations, the pandemic has marked a turning point in the history of scientific publishing [68]. Holden Thorp, the editor-in-chief of *Science*, said he encouraged authors to post their COVID-19 papers on preprint servers while they are under review at the journal. "Then, we're not deciding whether the world should or should not have the information. What we're deciding is whether this is an important part of the scientific record that should have the endorsement of our peer-review process" [69]. However, as some advocates called for increased use of preprints [70], many journals accelerated publication, and made their COVID-19 content free. Thus, although it seemed the long standing arguments for preprints (and open access) had increased resonance, the net effect of preprints on the system is an open question. To put this rapid evolution in context, we review the example of bioRxiv.

At the time of bioRxiv's launch in 2013, the most prominent preprint server was arXiv, which had a relatively small quantitative biology section [71], and PeerJ Preprints had only recently launched in the biological, medical, and environmental sciences [72]. bioRxiv differed from prior projects in a variety of ways: it was more selective; operated by a highly-respected, non-profit, scientific institution; had a more focused disciplinary identity; and offered the opportunity to tag results as "new," "contradictory," or "confirmatory," reflecting an aspiration to serve as a home for research papers that would be difficult to publish in journals [73]. At present there are more than 40 preprint servers that host medical and biomedical content [74], and many others outside the life sciences.

bioRxiv is widely considered a success [74] with policy changes by funders and universities having created incentives to post preprints [75], and the growth of new submissions following a geometric pattern [76] (at least until 2020). Journals prohibiting the posting of preprints in the basic life sciences are now few and far between, and many have established formal partnerships with bioRxiv to facilitate the simultaneous submission of manuscripts to the preprint server. Recently, the journal *eLife* has implemented a policy by which it will only review manuscripts that have been posted as preprints [51]. However, an increase in use and acceptance is not the only goal -- or the only outcome -- of the movement toward preprints in the life sciences.

Papers on bioRxiv appear a median of 4-5 months ahead of their publication date in a journal. Many appear only a month or two ahead of publication, suggesting that they are posted only after submission to a journal [78]. Nevertheless, any reduction in time to public disclosure can translate into an acceleration of scientific progress. In the case of the pandemic, more than ten thousand papers about COVID-19 were published in preprint form before appearing in journals in 2020 (in bioRxiv and its medical sibling, medRxiv), and early analysis showed they were shorter and had fewer references then other papers posted in the same period [7]. An analysis of COVID-19 research published in journals after appearing on bioRxiv or medRxiv showed the vast majority did not substantially change in their results and conclusions [79]. One interpretation of these results is that preprints were used to disseminate findings at an earlier stage in response to the crisis, reducing the time from discovery to reporting of reliable results – a hypothesis that deserves additional attention.

A significant factor promoting preprints is the potential for visibility earlier in the research cycle. In the case of the COVID-19 pandemic, preprints opened a voluminous conduit for transmitting early research to the public through the news media. In one prominent example, a preprint posted on medRxiv on April 7, 2020, showed that the vast majority of COVID-19 infections were transmitted indoors. The report was picked up by hundreds of news outlets [80] and tweeted almost 20,000 times (according to Altmetrics). It was published in the journal *Indoor Air* more than six months later [81], but by then it had already played a key role in shifting public understanding of how the virus is transmitted [82]. In another case, a counterfactual analysis of early non-pharmaceutical interventions to slow the spread of the virus, posted as a preprint on medRxiv, showed that tens of thousands of lives in the U.S. would have been saved by implementing non-pharmaceutical interventions one or two weeks earlier [83]. Posted on the preprint server in May, with data less than one month old, it was reported prominently by the *New York Times*, with dramatic graphics [84], and hundreds of other outlets (according to Altmetrics). The version that was subsequently published by *Science Advances* -- the relatively rapid outlet for *Science*, appeared more than 6 months later, and drew much less attention (the results were substantially similar but not identical) [85]. Despite some dramatic cases, the systematic effect of preprints on influencing public understanding and policy has not yet been established – especially in light of other changes made at the same time by researchers, journal editors, and the news media, at the same time. And there are counterexamples. In a dramatic case of incorrect findings having a potential negative impact when released without peer review, a preprint claiming to find “uncanny similarity” between SARS-CoV-2 and HIV was posted to bioRxiv on January 31, 2020. However, it was withdrawn two days later after other scientists immediately discovered errors in its analysis [86].

Clearly, early visibility can have positive consequences, such as garnering recognition for grants, jobs, and collaborations. Preprinting is associated with an increase in both Altmetric “attention scores” and journal citations [87,88]. Public commenting on preprints can aid in visibility and filtering, and acts as publicly-disclosed feedback to authors. Whether in public or not, early response to preprints has the potential to improve the overall quality of the literature by enabling authors to revise their work. However, the extent to which such potential has been realized remains unknown.

Finally, although many servers subject preprints to screening before posting, this process is usually much less selective than journal peer review. Posting preprints is generally free, and, because of the light screening process, it is inexpensive in terms of time and energy as well. If researchers compete at least in part on volume of outputs, it is likely that the availability of preprint services and the legitimacy of preprints would increase the fraction of research made public. Indeed, as of 2019 approximately 30% of papers on bioRxiv did not subsequently appear in a journal [89]. And just under 25% of papers related to COVID-19 published during the first six months of the pandemic appeared in a journal within four months [90]. This implies that preprints are leading to a greater volume of research being made public than the journal system alone, which is seen as an advantage by those who view the gatekeeping of journals as biased or limiting in undesirable ways (for example by filtering out negative results and contradictory findings). Again, however, we lack the capacity – especially with regard to measuring research output in a consistent way across time – that would be necessary to evaluate this conclusion.

4.3 Potential Unanticipated effects of preprints

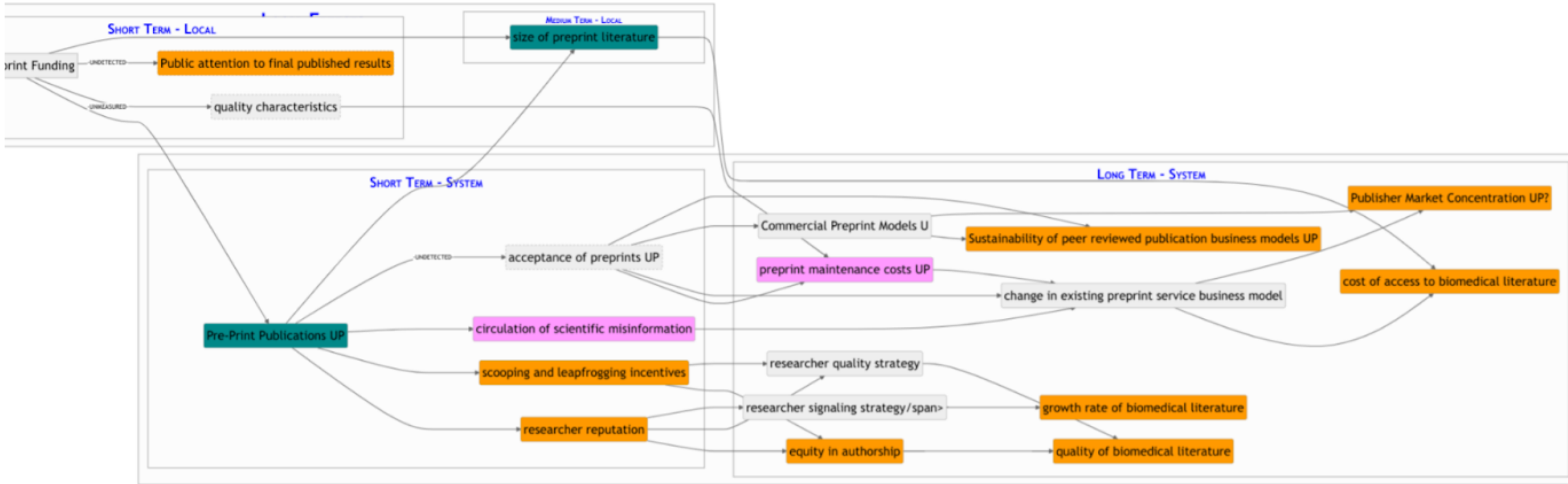


Figure 4: Potential Unanticipated Effects of Preprint Services

As the use of preprints has mushroomed, especially within the life sciences, a wide range of concerns and problems have been raised [91]. Here we categorize these issues according to the scheme used for APCs above: unobserved outcomes, unmeasured characteristics, systemic effects, and long-run dynamics.

Preprints offer a solution to the problem of paywalled access to research publications held by journals, by serving free copies of manuscripts, usually in an early version. In fact, the founders of bioRxiv have argued that research funders should implement a so-called Plan U (for "universal"), requiring their grantees to post preprints of all published work [92]. However, this raises the possibility of an *unobserved outcome*, that readers who rely on preprints because they're freely available won't read the subsequent journal versions that are behind paywalls (what publishers call the "version of record"), which are at least sometimes improved over the preprint version. We might ask, then, whether preprints reinforce a knowledge gap between those who have access to paywalled journal articles and those who do not.

Assessing the short and long-term implications of preprints is complicated by the likelihood of selection bias among the researchers who post them, which is also unobserved. On one hand, better-resourced scientists may post preprints because they have higher confidence in their early work. But on the other hand, those with fewer resources may use preprints as a way to reach readers with work they can't publish in peer-reviewed journals. The balance of such preferences -- which itself may vary across disciplines and fields -- remains unknown. It is possible to compare preprint and journal publications of the same paper (e.g., [79]), but we have no capacity to gather and analyze this systematically.

Assessing the quality of preprints, and their potential systemic impact on the quality of published science, is difficult because they represent a different form of science communication from journal articles. This represents a set of *unmeasured characteristics* in the system. Thus, if the number of unreliable preprints is added to the numerator in the ratio of bad science production, and all preprints go in the denominator, what does that rate tell us? If a high proportion of preprints are bad, that might lead to success in identifying errors and problems early in the publication process, or might indicate the problem of making flawed science public. When the overall quality of scientific research is a fraught policy issue, and every bad study becomes potential fodder for political demagoguery against science itself, the stakes in such calculations are high. The problem of evaluating the overall quality of science is not new or unique to preprints, but preprints present a flood of new information with uncertain implications for the question.

When researchers' behavior with regard to preprints affects others, the result could be unanticipated *systemic effects*. The greater visibility of early work distributed in preprint form may have negative consequences for those who post them. For example, a preprint might alert competitors to the presence of the work, inducing them to change their own research and publication plans. Less-established researchers may be concerned about their ability to beat better-resourced labs through the necessary experiments and publication process [93]. If journals (such as Nature journals [94]) do not consider a pre-existing preprint as a "prior publication," that could compound such disadvantages. Just as public health interventions can overlook or exploit disadvantaged groups, open science interventions may offer benefits to those who are already well-positioned within the research ecosystem. Preprints place authors in a position of vulnerability because their work is shared early, but in ways for which they might not be institutionally rewarded – and status recognition practices that rely on journal publications exacerbate this risk. In addition, well-established investigators may use perprints to garner visibility as a result of their name recognition, while junior scholars' preprints remain undiscovered [95]. Thus, preprint posting has the potential to exacerbate systemic inequalities.

Like dentists driven out of business by fluoridation, the sudden availability of public goods (or public information) can create *long-run dynamics* that disrupt existing business models. In the case of preprints, they might help challenge the dominance of corporate publishers. If preprint versions of papers are available, the subscription or APC models of generating profits for publishers might be undermined. However, the leading publishers seem well prepared for such an eventuality, as they are creating their own preprint and preprint-adjacent services. For example, authors at some Springer Nature journals are offered the opportunity to use the In Review service, which allows them to share preprints while papers are under review [96]. Cell Press offers authors Sneak Peek, which is essentially a preprint service [97]. Another is Sage Advance, a "preprints community" for social sciences and humanities, which attempts to capture papers for submission to Sage journals [98]. On the other hand, preprint services -- operating as free for both authors and readers -- do not have a clear path to sustainability beyond the philanthropic funding streams that have allowed them to thrive thus far [91]. Thus, the disruption of the current publishing model may not always work in favor of preprints.

4.4 Design

The majority of interventions in open science are launched as iterative exploratory activities without a systematic treatment or measurement framework. In the case of preprints, a simple assessment based on the flow of research through major servers signals success of the specific initiatives, but if there are unanticipated systemic consequences, that success might not imply overall benefits to production and dissemination of knowledge. Critics already complain that disseminating research without prior peer review threatens public health [100], in which case the success of the preprint intervention would perversely imply negative effects on a growing scale. Developers of any one intervention aren't responsible for assessing all possible system effects of their work. But their interests are probably broader than a narrow uptake or revenue analysis implies. We need to develop mechanisms for asking and answering questions on a scale somewhere in between the immediate effects of a given intervention and the universe of possible system effects. Funders may not be enthusiastic to support assessments of possible effects that are far removed from an individual project, but the research community has an interest in wider understanding. Successfully addressing such questions will require community-based assessments that different researchers can use to study the impact of specific interventions. Done right, this may also mitigate the problem of self-interested assessments, and allow better documentation of failures (for example, after the staff of an unsuccessful project is let go).

Analyses of scholarly communication have generated calls for systemic reforms [101,102]. However, the system is prone to unintended consequences even when interventions are well-measured and appear to make incremental improvements. Over the last two decades, the practice of science communication has advanced through the efforts of individual communities and stakeholders to make science more open, transparent, and reliable. Thus, many interventions have been designed and deployed with a primary focus on operational and advocacy concerns -- and evaluation of these efforts are primarily observational and retrospective. While this is not a formal research design, it appears as a common *design pattern* [103,104], which we label "Do It Now, Check Sometime" (DOINCS).

Actors in the throes of innovation frequently are called upon to make in-stream modifications of their systems without incorporating comprehensive assessment plans or threat analyses. For example, as the pandemic unfolded, bioRxiv created a collection of papers related to COVID-19 (available at: COVID-19 SARS-CoV-2 preprints from medRxiv and bioRxiv). At first it was a simple list of related papers.

However, after accumulating approximately 2000 articles, they added a disclaimer at the top of the page clarifying that the preprints are not peer reviewed and should not be considered conclusive, a disclaimer that was subsequently further revised. In another case, the creators of *Rapid Reviews: COVID-19* implemented an overlay journal providing assessment of pandemic-related papers posted on preprint servers, which posted reviews of papers independent of the authors who wrote them [105], combining a publishing innovation with an expert intervention into the evolving literature. These changes in preprint communications are just examples of the rolling modifications and innovations that organizations routinely make. But in this case they occurred in the middle of what is also a large, uncontrolled experiment in scientific dissemination, in which the perceptions of reliability and peer review around preprints are being closely scrutinized – and the public health stakes are high. Although it is impossible to anticipate all possibilities in complex systems (by their nature), without design principles in place to capture and assess data from an evolving intervention, the opportunity for systematic analysis and understanding (difficult in the best of circumstances) may be lost.

In the case of bioRxiv, fortunately, the services papers and their metadata are available for systematic analysis, allowing them to be compared to subsequently published versions, and linked to other sources for analysis, such as Retraction Watch's COVID-19 database [106], Altmetrics, and news media databases. Thus, it may be possible to study the trace effects of specific preprint reporting practices. However, to begin to describe the full dynamics of preprints within the system of scholarly communication would require systematic data from outside the preprint workflow as well, involving, for example, attitudes and behaviors of researchers, institutional responses, the impact of preprints in the public sphere, the effects of preprinting on academic careers, and so on (such research design and data needs are beyond the scope of this paper).

The history of public health interventions demonstrates that retrospective descriptive analysis is insufficient to yield the depth of causal understanding needed to effect desirable change. Understanding the causal impact of different preprint initiatives will require more than describing the dynamics of the scholarly communications ecosystem over time -- it will also require that we be able to link changes in these dynamics to initiatives and interventions. Interventions in public health are designed not only to inform short-term local evaluation needs (e.g., by measuring disease reduction in the treated sample), but also to be comparable with other interventions (e.g., by providing standardized measures of risk reduction, and demographic correlates), to contribute to a global evidence base (e.g., through reporting to a global indicators program), and to provide reliable evidence for evaluating causal effects (e.g., through field experiments and randomization). Scholarly communication needs to learn from these methods.

5 DISCUSSION

The COVID-19 pandemic interrupted many aspects of science and social life simultaneously. By the time it arrived we were already decades into the intervention of preprints in scholarly communication, and still without a systematic understanding of how they have contributed to the changing ecosystem. Like DDT or the other public health examples mentioned above, and like the APC model of open access publishing, preprints clearly have generated direct effects -- as can be measured by their growing presence in the scholarly record -- but also indirect and unintended effects that we may not be able to systematically assess. Our conclusion from this review is that although we can learn by doing, if we want deeper understanding we have to design our interventions to be studied, and then study the implementation of those designs. There are recent examples of systemic assessments of open science practices, but these are usually post hoc in nature (e.g., [107,108]). Other proposals for large-scale experimental studies are in the developmental stage (e.g., [109]). Despite these exceptions, interventions in the scholarly ecosystem predominantly follow the pattern of "do it now, check sometimes." Under favorable conditions, these interventions can provide substantial information about what works in science communication. If eventual analyses are shared, they may offer opportunities for future innovators to learn from past efforts. However, as research in public health suggests, in complex interdependent ecosystems the outcomes from DOINCS often do not generalize, are difficult to compare, and are often misleading.

Naturally, the issues raised by APC open access, and the bioRxiv and medRxiv preprint servers, do not span the entire range of challenges to open science. To the contrary, generalizing from these cases is made easier by their highly visible, well-funded, and apparently successful nature. The majority of changes in science and publishing are probably smaller, occur behind the scenes, and have less immediate and demonstrable effects. However, complex systems are inherently unmanageable. As preprints illustrate, even when there is general agreement that an open science intervention works -- for example, through growing uptake -- there may be no systematic measurement of its impact, nor a robust understanding of the reasons for its success. APCs and preprints are simply some of the most visible of many interventions in science and scholarly communication practice.

The history of public health strongly suggests that we can only mitigate unwanted and potentially severe downstream consequences in scholarly communication by developing better systemic understanding of open science interventions. We suggest several broad approaches drawing from this history. First, identify key measures of practices and outcomes – beyond program uptake, revenue, user satisfaction, and other narrow indicators – to be used across interventions and assessments. Second, develop the infrastructure needed for data collection and only sharing these measures across the system, and condition support for new interventions on its use. Third, build research assessment into the foundation of new initiatives, using the standards of intervention research. Finally, prioritize the construction and deployment of theories of systemic change, making explicit the connections between projects across space and time. Scholarly communications needs an open, global data system for monitoring and evaluation, one we believe could be modeled on public health data systems. Such a system would comprise a set of desirable and adverse outcomes, based on comparable measures, with consistent tracking and open data. Under such a system, each intervention can contribute cumulatively to new knowledge.

We agree that change is needed, and there are real costs to inaction. Scholarly communication in science is too slow [93], too expensive [110], and dominated by the concerns of powerful actors – publishers, universities, and governments – in wealthy industrialized nations [111]. In addition, problems of trust undermine public confidence in science, which is increasingly a partisan issue [112]. All of these threats to the system may have been exacerbated by the COVID-19 pandemic, which has tested scientific authorities making life and death decisions working on limited budgets. Perfection is not a reasonable goal, and real-world developments can threaten any well-planned intervention, but careful design to capture systemic effects is essential to understanding and improving the impact of our efforts.

6 ACKNOWLEDGMENTS

We describe contributions to the paper using a standard taxonomy (see Allen L, Scott J, Brand A, Hlava M, Altman M. Publishing: Credit where credit is due. Nature. 2014;508(7496):312-3.). All authors take equal responsibility for the article in its current form. All authors collaborated in creating the first draft of the manuscript; All authors contributed to review and revision. All authors contributed to the conception of the article (including core ideas, analytical framework, and statement of research questions). All authors contributed to the project administration and to the writing process through direct writing, critical review, and commentary. We thank Richard Sever, David Weinberger, and members of the CREOS research seminar for comments on earlier drafts.

7 COMPETING INTERESTS

The authors have no substantial conflicts of interest but wish to thank the Sloan Foundation, Chan-Zuckerberg Initiative, and IMLS (award LG-250130-OLS-21) for their research support.

8 REFERENCES

1. Independent Panel for Pandemic Preparedness and Response. Second Report on Progress. World Health Organization; 2021. Available: https://theindependentpanel.org/wp-content/uploads/2021/01/Independent-Panel_Second-Report-on-Progress_Final-15-Jan-2021.pdf
2. Committee on Toward an Open Science Enterprise, Board on Research Data and Information, Policy and Global Affairs, National Academies of Sciences, Engineering, and Medicine. Open Science by Design: Realizing a Vision for 21st Century Research. Washington, D.C.: National Academies Press; 2018. doi:10.17226/25116
3. Allen L, Scott J, Brand A, Hlava M, Altman M. Publishing: Credit where credit is due. Nature. 2014;508: 312–313. doi:10.1038/508312a
4. National Academies of Sciences E. Open Science by Design: Realizing a Vision for 21st Century Research. 2018. doi:10.17226/25116
5. Wilkinson MD, Dumontier M, Aalbersberg IjJ, Appleton G, Axton M, Baak A, et al. The FAIR Guiding Principles for scientific data management and stewardship. Sci Data. 2016;3: 160018. doi:10.1038/sdata.2016.18
6. Nosek BA, Alter G, Banks GC, Borsboom D, Bowman SD, Breckler SJ, et al. Promoting an open research culture. Science. 2015;348: 1422–1425. doi:10.1126/science.aab2374
7. Fraser N, Brierley L, Dey G, Polka JK, Pálfy M, Nanni F, et al. The evolving role of preprints in the dissemination of COVID-19 research and their impact on the science communication landscape. PLOS Biol. 2021;19: e3000959. doi:10.1371/journal.pbio.3000959
8. Yan W. Coronavirus Tests Science’s Need for Speed Limits. The New York Times. 14 Apr 2020. Available: https://www.nytimes.com/2020/04/14/science/coronavirus-disinformation.html. Accessed 28 May 2020.
9. Ginsparg P. Lessons from arXiv’s 30 years of information sharing. Nat Rev Phys. 2021;3: 602–603. doi:10.1038/s42254-021-00360-z
10. Kim S-J, Park KS. Open access status of journals and articles in Journal Citation Reports. Sci Ed. 2021;8: 26–31. doi:10.6087/kcse.226
11. Elsevier. Elsevier Journal and Article Ecosystem. 2022 Jan. Available: https://web.archive.org/web/20220603090311/https://www.elsevier.com/__data/assets/pdf_file/0010/616474/Journal-and-article-ecosystem-2021.pdf
12. Baldwin M. Scientific Autonomy, Public Accountability, and the Rise of “Peer Review” in the Cold War United States. Isis. 2018;109: 538–558. doi:10.1086/700070

13. Altman M. Designing Community Tracking Indicators for Open and Inclusive Scholarship. MetaArXiv; 2022 May. doi:10.31222/osf.io/z495g
14. Priem J, Piwowar H, Orr R. OpenAlex: A fully-open index of scholarly works, authors, venues, institutions, and concepts. 2022 [cited 1 Aug 2022]. doi:10.48550/ARXIV.2205.01833
15. Tsuji K. Statistics on Open Access Books Available through the Directory of Open Access Books. 2018 [cited 1 Aug 2022]. doi:10.48550/ARXIV.1808.01541
16. Nishikawa-Pacher A, Heck T, Schoch K. Open Editors: A Dataset of Scholarly Journals' Editorial Board Positions. SocArXiv; 2021 Mar. doi:10.31235/osf.io/jvzq7
17. Hammonds R, Hanefeld J, Ooms G. Accountability as a driver of health equity. Copenhagen: WHO Regional Office for Europe; 2019. Available: https://apps.who.int/iris/bitstream/handle/10665/312282/9789289054096-eng.pdf
18. Mabaso MLH, Sharp B, Lengeler C. Historical review of malarial control in southern African with emphasis on the use of indoor residual house-spraying. Trop Med Int Health. 2004;9: 846–856. doi:10.1111/j.1365-3156.2004.01263.x
19. Carson R. Silent Spring. Fawcett; 1962.
20. O'Shaughnessy PT. PARACHUTING CATS AND CRUSHED EGGS The Controversy Over the Use of DDT to Control Malaria. Am J Public Health. 2008;98: 1940–1948. doi:10.2105/AJPH.2007.122523
21. Green JM. The rise and future of glyphosate and glyphosate-resistant crops. Pest Manag Sci. 2018;74: 1035–1039. doi:10.1002/ps.4462
22. Kupferschmidt K. After 40 years, the most important weapon against mosquitoes may be failing. In: Science | AAAS [Internet]. 13 Oct 2016 [cited 5 Aug 2021]. Available: https://www.sciencemag.org/news/2016/10/after-40-years-most-important-weapon-against-mosquitoes-may-be-failing
23. Beard J. DDT and human health. Sci Total Environ. 2006;355: 78–89. doi:10.1016/j.scitotenv.2005.02.022
24. van den Berg H. Global Status of DDT and Its Alternatives for Use in Vector Control to Prevent Disease. Environ Health Perspect. 2009;117: 1656–1663. doi:10.1289/ehp.0900785
25. van den Berg H, Manuweera G, Konradsen F. Global trends in the production and use of DDT for control of malaria and other vector-borne diseases. Malar J. 2017;16: 401. doi:10.1186/s12936-017-2050-2
26. Tubbs CW. California condors and DDT: Examining the effects of endocrine disrupting chemicals in a critically endangered species. Endocr Disruptors. 2016;4: e1173766. doi:10.1080/23273747.2016.1173766
27. World Health Organization. World Malaria Report 2020. Geneva: WHO; 2020. Available: https://www.who.int/publications-detail-redirect/9789240015791
28. Short R, Gurung R, Rowcliffe M, Hill N, Milner-Gulland EJ. The use of mosquito nets in fisheries: A global perspective. PLOS ONE. 2018;13: e0191519. doi:10.1371/journal.pone.0191519
29. Ho K, Neidell M. Equilibrium effects of public goods: The impact of community water fluoridation on dentists. National Bureau of Economic Research; 2009 Jun. Report No.: 15056. doi:10.3386/w15056
30. Hedlund J. Risky business: safety regulations, risk compensation, and individual behavior. Inj Prev. 2000;6: 82–89. doi:10.1136/ip.6.2.82
31. Cassell MM, Halperin DT, Shelton JD, Stanton D. Risk compensation: the Achilles' heel of innovations in HIV prevention? BMJ. 2006;332: 605–607. doi:10.1136/bmj.332.7541.605

32. Alsan M, Wanamaker M. Tuskegee and the Health of Black Men. Q J Econ. 2018;133: 407–455. doi:10.1093/qje/qjx029
33. AbouZahr C, Boerma T. Health information systems: the foundations of public health. Bull World Health Organ. 2005;83: 578–583. doi:/S0042-96862005000800010
34. Thacker SB, Stroup DF. Future Directions for Comprehensive Public Health Surveillance and Health Information Systems in the United States. Am J Epidemiol. 1994;140: 383–397. doi:10.1093/oxfordjournals.aje.a117261
35. Choi BCK. The Past, Present, and Future of Public Health Surveillance. Scientifica. 2012;2012: e875253. doi:10.6064/2012/875253
36. Uniform requirements for manuscripts submitted to biomedical journals: Writing and editing for biomedical publication. J Pharmacol Pharmacother. 2010;1: 42–58.
37. Moher D, Hopewell S, Schulz KF, Montori V, Gøtzsche PC, Devereaux PJ, et al. CONSORT 2010 explanation and elaboration: Updated guidelines for reporting parallel group randomised trials. Int J Surg. 2012;10: 28–55. doi:10.1016/j.ijsu.2011.10.001
38. Simera I, Moher D, Hirst A, Hoey J, Schulz KF, Altman DG. Transparent and accurate reporting increases reliability, utility, and impact of your research: reporting guidelines and the EQUATOR Network. BMC Med. 2010;8: 24. doi:10.1186/1741-7015-8-24
39. Kiley R, Peatfield T, Hansen J, Reddington F. Data Sharing from Clinical Trials — A Research Funder's Perspective. N Engl J Med. 2017;377: 1990–1992. doi:10.1056/NEJMsb1708278
40. Sharing Clinical Trial Data: Maximizing Benefits, Minimizing Risk. Washington, D.C.: National Academies Press; 2015. p. 18998. doi:10.17226/18998
41. Jorgenson LA, Wolinetz CD, Collins FS. Incentivizing a New Culture of Data Stewardship: The NIH Policy for Data Management and Sharing. JAMA. 2021;326: 2259. doi:10.1001/jama.2021.20489
42. Koo D, Wetterhall SF. History and current status of the national notifiable diseases surveillance system. J Public Health Manag Pract. 1996; 4–10.
43. Framework for program evaluation in public health. MMWR Recomm Rep Morb Mortal Wkly Rep Recomm Rep. 1999;48: 1–40.
44. Moher D. Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. Ann Intern Med. 2009;151: 264. doi:10.7326/0003-4819-151-4-200908180-00135
45. Teytelman L, Stoliartchouk A, Kindler L, Hurwitz BL. Protocols.io: Virtual Communities for Protocol Development and Discussion. PLOS Biol. 2016;14: e1002538. doi:10.1371/journal.pbio.1002538
46. Banerjee A, Duflo E, editors. Handbook of economic field experiments. Amsterdam, Netherlands: North-Holland, An imprint of Elsevier; 2017.
47. Victora CG, Habicht J-P, Bryce J. Evidence-Based Public Health: Moving Beyond Randomized Trials. Am J Public Health. 2004;94: 400–405. doi:10.2105/AJPH.94.3.400
48. Rothman KJ, Lash TL, VanderWeele TJ, Haneuse S. Modern epidemiology. Fourth edition. Philadelphia: Wolters Kluwer; 2021.
49. Glanz K, Bishop DB. The Role of Behavioral Science Theory in Development and Implementation of Public Health Interventions. Annu Rev Public Health. 2010;31: 399–418. doi:10.1146/annurev.publhealth.012809.103604
50. Valente TW, Pitts SR. An Appraisal of Social Network Theory and Analysis as Applied to Public Health: Challenges and Opportunities. Annu Rev Public Health. 2017;38: 103–118. doi:10.1146/annurev-publhealth-031816-044528
51. Birkhead GS, Morrow CB, Pirani S. Turnock's public health: what it is and how it works.

Seventh edition. Burlington, MA: Jones & Bartlett Learning; 2022.
52. Budapest Open Access Initiative. Read the Declaration. 14 Feb 2002 [cited 5 Apr 2022]. Available: https://www.budapestopenaccessinitiative.org/read/
53. Public Library of Science: PLoS Launches PLoS Biology. In: PLOS [Internet]. 16 Oct 2003 [cited 23 Nov 2021]. Available: https://web.archive.org/web/20031016063325/https://plos.org/news/announce_pbiolaunch.html
54. Delamothe T, Godlee F, Smith R. Scientific literature's open sesame? BMJ. 2003;326: 945–946.
55. McKenzie L. Big Deal for Open Access. In: Inside Higher Ed [Internet]. 17 Mar 2021 [cited 15 Mar 2022]. Available: https://www.insidehighered.com/news/2021/03/17/university-california-reaches-new-open-access-agreement-elsevier
56. Brainard J. For €9500, Nature journals will now make your paper free to read. Science. 2020 [cited 25 Apr 2022]. doi:10.1126/science.abf8491
57. Schönfelder N. Article processing charges: Mirroring the citation impact or legacy of the subscription-based model? Quant Sci Stud. 2020;1: 6–27. doi:10.1162/qss_a_00015
58. Siler K. Demarcating spectrums of predatory publishing: Economic and institutional sources of academic legitimacy. J Assoc Inf Sci Technol. 2020;71: 1386–1401. doi:10.1002/asi.24339
59. Nabyonga-Orem J, Asamani JA, Nyirenda T, Abimbola S. Article processing charges are stalling the progress of African researchers: a call for urgent reforms. BMJ Specialist Journals; 2020.
60. García JA, Rodriguez-Sánchez R, Fdez-Valdivia J. Quality censoring in peer review. Scientometrics. 2021;126: 825–830.
61. Smith M, Anderson I, Bjork B-C, McCabe M, Solomon D, Tananbaum G, et al. Pay it forward: Investigating a sustainable model of open access article processing charges for large north american research institutions. 2016.
62. Parsons D, Willis D, Holland J. Benefits to the private sector of open access to higher education and scholarly research. UK Open Access Implement Group. 2011.
63. Brainard J. California universities and Elsevier make up, ink big open-access deal. Science. 16 Mar 2021. Available: https://www.science.org/content/article/california-universities-and-elsevier-make-ink-big-open-access-deal. Accessed 9 Nov 2021.
64. Shen C, Björk B-C. 'Predatory' open access: a longitudinal study of article volumes and market characteristics. BMC Med. 2015;13: 230. doi:10.1186/s12916-015-0469-2
65. Laakso M, Björk B-C. Anatomy of open access publishing: a study of longitudinal development and internal structure. BMC Med. 2012;10: 1–9.
66. Price GD, Chaytor S. Open Access: Is a National Licence the Answer? Higher Education Policy Institute; 2015.
67. Poynder R. Open access publishing – Beyond Plan S for the Global South. In: University World News: The Global Window on Higher Education [Internet]. 2019. Available: https://www.universityworldnews.com/post.php?story=20190422104333956
68. Callaway E. Will the pandemic permanently alter scientific publishing? Nature. 2020 [cited 4 Jun 2020]. doi:10.1038/d41586-020-01520-4
69. Tingley K. Coronavirus Is Forcing Medical Research to Speed Up. The New York Times. 21 Apr 2020. Available: https://www.nytimes.com/2020/04/21/magazine/coronavirus-scientific-journals-research.ht

ml. Accessed 21 May 2020.
70. Wellcome. Coronavirus (COVID-19): sharing research data. In: Wellcome [Internet]. 30 Jan 2020 [cited 9 Nov 2021]. Available: https://wellcome.org/press-release/sharing-research-data-and-findings-relevant-novel-coronavirus-ncov-outbreak
71. Quantitative Biology: Article Statistics for 2013. In: arxiv.org [Internet]. 2013 [cited 4 Jun 2020]. Available: https://arxiv.org/year/q-bio/13
72. PeerJ Staff. 'PeerJ PrePrints' – a new Preprint Server for the Biological and Medical Sciences. In: PeerJ blog [Internet]. 3 Apr 2013 [cited 4 Jun 2020]. Available: https://peerj.com/blog/post/47030855181/peerj-preprints-a-new-preprint-server-for-the-biological-and-medical-sciences/
73. Kaiser J. New Preprint Server Aims to Be Biologists' Answer to Physicists' arXiv. In: Science [Internet]. 12 Nov 2013 [cited 4 Jun 2020]. Available: https://www.sciencemag.org/news/2013/11/new-preprint-server-aims-be-biologists-answer-physicists-arxiv
74. Kirkham JJ, Penfold N, Murphy F, Boutron I, Ioannidis JP, Polka JK, et al. A systematic examination of preprint platforms for use in the medical and biomedical sciences setting. bioRxiv. 2020; 2020.04.27.063578. doi:10.1101/2020.04.27.063578
75. Funder policies. In: ASAPbio [Internet]. [cited 15 Jan 2021]. Available: https://asapbio.org/funder-policies
76. Sever R, Roeder T, Hindle S, Sussman L, Black K-J, Argentine J, et al. bioRxiv: the preprint server for biology. bioRxiv; 2019. p. 833400. doi:10.1101/833400
77. Eisen MB, Akhmanova A, Behrens TE, Harper DM, Weigel D, Zaidi M. Implementing a "publish, then review" model of publishing. eLife. 2020;9: e64910. doi:10.7554/eLife.64910
78. Levchenko M. Preprints in Europe PMC: reducing friction for discoverability. In: Europe PMC [Internet]. 11 Jul 2018 [cited 19 Jan 2021]. Available: http://blog.europepmc.org/2018/07/preprints.html
79. Polka JK, Dey G, Pálfy M, Nanni F, Brierley L, Fraser N, et al. Preprints in motion: tracking changes between posting and journal publication. bioRxiv. 2021; 2021.02.20.432090. doi:10.1101/2021.02.20.432090
80. Levenson M, Parker-Pope T, Gorman J. What We Know About Your Chances of Catching the Virus Outdoors. The New York Times. 15 May 2020. Available: https://www.nytimes.com/2020/05/15/us/coronavirus-what-to-do-outside.html. Accessed 9 Feb 2021.
81. Qian H, Miao T, Liu L, Zheng X, Luo D, Li Y. Indoor transmission of SARS-CoV-2. medRxiv. 2020; 2020.04.04.20053058. doi:10.1101/2020.04.04.20053058
82. Tufekci Z. We Need to Talk About Ventilation. In: The Atlantic [Internet]. 30 Jul 2020 [cited 9 Feb 2021]. Available: https://www.theatlantic.com/health/archive/2020/07/why-arent-we-talking-more-about-airborne-transmission/614737/
83. Pei S, Kandula S, Shaman J. Differential Effects of Intervention Timing on COVID-19 Spread in the United States. medRxiv. 2020; 2020.05.15.20103655. doi:10.1101/2020.05.15.20103655
84. Glanz J, Robertson C. Lockdown Delays Cost at Least 36,000 Lives, Data Show. The New York Times. 21 May 2020. Available: https://www.nytimes.com/2020/05/20/us/coronavirus-distancing-deaths.html. Accessed 21 Sep 2021.
85. Pei S, Kandula S, Shaman J. Differential effects of intervention timing on COVID-19

spread in the United States. Sci Adv. 2020;6: eabd6370. doi:10.1126/sciadv.abd6370
86. Pradhan P, Pandey AK, Mishra A, Gupta P, Tripathi PK, Menon MB, et al. Uncanny similarity of unique inserts in the 2019-nCoV spike protein to HIV-1 gp120 and Gag. bioRxiv. 2020; 2020.01.30.927871. doi:10.1101/2020.01.30.927871
87. Preprint stories. In: ASAPbio [Internet]. [cited 19 Jan 2021]. Available: https://asapbio.org/preprint-info/preprint-stories
88. Fu DY, Hughey JJ. Releasing a preprint is associated with more attention and citations for the peer-reviewed article. bioRxiv. 2019; 699652. doi:10.1101/699652
89. Abdill RJ, Blekhman R. Tracking the popularity and outcomes of all bioRxiv preprints. Pewsey E, Rodgers P, Greene CS, editors. eLife. 2019;8: e45133. doi:10.7554/eLife.45133
90. Kodvanj I, Homolak J, Virag D, Trkulja V. Publishing of COVID-19 Preprints in Peer-reviewed Journals, Preprinting Trends, Public Discussion and Quality Issues. bioRxiv. 2020; 2020.11.23.394577. doi:10.1101/2020.11.23.394577
91. Puebla I, Polka J, Rieger OY. Preprints: Their Evolving Role in Science Communication. MetaArXiv; 2021. doi:10.31222/osf.io/ezfsk
92. Sever R, Eisen M, Inglis J. Plan U: Universal access to scientific and medical research via funder preprint mandates. PLOS Biol. 2019;17: e3000273. doi:10.1371/journal.pbio.3000273
93. Sarabipour S, Debat HJ, Emmott E, Burgess SJ, Schwessinger B, Hensel Z. On the value of preprints: An early career researcher perspective. PLOS Biol. 2019;17: e3000151. doi:10.1371/journal.pbio.3000151
94. Preprints & Conference Proceedings. In: Nature Research [Internet]. [cited 19 Jan 2021]. Available: https://www.nature.com/nature-research/editorial-policies/preprints-and-conference-proceedings
95. Faulkes Z. NeuroDojo: A pre-print experiment: will anyone notice? In: NeuroDojo [Internet]. 17 Mar 2016 [cited 17 Aug 2021]. Available: http://neurodojo.blogspot.com/2016/03/a-pre-print-experiment-will-anyone.html
96. Springer Nature. In Review | SpringerNature | Authors | Springer Nature. [cited 15 Jul 2021]. Available: https://www.springernature.com/gp/authors/campaigns/in-review
97. Cell Press. Cell Press Sneak Peek :: SSRN. [cited 15 Jul 2021]. Available: https://www.ssrn.com/index.cfm/en/cell-press-sneak-peek/
98. Sage. advance: a SAGE preprints community - Browse. [cited 15 Jul 2021]. Available: https://advance.sagepub.com/
99. Gough NR. Preprints as Final Publication. In: BioSerendipity [Internet]. 26 Feb 2019 [cited 17 Aug 2021]. Available: https://www.bioserendipity.com/preprints-as-final-publication/
100. Majumder MS, Mandl KD. Early in the epidemic: impact of preprints on global discourse about COVID-19 transmissibility. Lancet Glob Health. 2020;8: e627–e630. doi:10.1016/S2214-109X(20)30113-3
101. Nature. Challenges in irreproducible research. 2018 Oct. Available: https://www.nature.com/collections/prbfkwmwvz
102. Altman M, Bourg C. A Grand Challenges-Based Research Agenda for Scholarly Communication and Information Science. 2018 [cited 19 Dec 2019]. doi:10.21428/62b3421f
103. Alexander C. The Timeless Way of Building. New York, NY: Oxford University Press; 1979.
104. Pree W. Design Patterns for Object-Oriented Software Development. 1st edition. Wokingham, England ; Reading, Mass: Addison-Wesley; 1994.
105. RR:C19. FAQ · Rapid Reviews COVID-19. In: Rapid Reviews COVID-19 [Internet]. [cited

16 Nov 2021]. Available: https://rapidreviewscovid19.mitpress.mit.edu/faq
106. Retracted coronavirus (COVID-19) papers. In: Retraction Watch [Internet]. 29 Apr 2020 [cited 21 Sep 2021]. Available: https://retractionwatch.com/retracted-coronavirus-covid-19-papers/
107. Piwowar H, Priem J, Larivière V, Alperin JP, Matthias L, Norlander B, et al. The state of OA: a large-scale analysis of the prevalence and impact of Open Access articles. PeerJ. 2018;6: e4375. doi:10.7717/peerj.4375
108. Momeni F, Fraser N, Peters I, Mayr P. From closed to open access: A case study of flipped journals. ArXiv190311682 Cs. 2019 [cited 2 May 2022]. Available: http://arxiv.org/abs/1903.11682
109. Nosek BA, Mellor DT, Errington TM, Soderberg CK, Krall T, Grasty FL, et al. NSF Science of Science Proposal: Randomized Trial of Registered Reports. MetaArXiv; 2020. doi:10.31222/osf.io/jvxab
110. Wenzler J. Scholarly Communication and the Dilemma of Collective Action: Why Academic Journals Cost Too Much | Wenzler | College & Research Libraries. Coll Res Libr. 2017;78. doi:https://doi.org/10.5860/crl.78.2.183
111. Collyer FM. Global patterns in the publishing of academic knowledge: Global North, global South. Curr Sociol. 2018;66: 56–73. doi:10.1177/0011392116680020
112. Cohen PN. The widening political divide over science. 2018 [cited 28 May 2020]. doi:10.31235/osf.io/u95aw