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

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1 ABSTRACT

The COVID-19 pandemic is an exemplar of how scholarly communication can change in response to external shocks, even as the scholarly knowledge ecosystem is evolving rapidly, and many argue that swift and fundamental interventions are needed. However, it is much easier to identify ongoing changes and emerging interventions than to understand their immediate and long term impacts. This is illustrated by comparing the approaches applied by the scientific community to understand public health risks and interventions with those applied by the scholarly communications community to the science of COVID-19. 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 the methodology of analysis and intervention developed 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 four threats apply lead to the last major intervention in scholarly publication -- the article publishing charge based open access model -- to yield surprising results. Finally, we outline how these four threats may affect the impact of preprint initiatives, and we identify approaches drawn from public health to mitigate these threats.

2 INTRODUCTION

The scholarly ecosystem is evolving rapidly, and many argue that swift and 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 [1]; how researchers are trained and credited [2]; how research is planned and designed [3]; how evidence is collected, managed, and shared [4]; and how research findings are published, cited, and replicated [5]. 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 increase in use of preprints, as scientists sought to push their research forward more rapidly [6], and to a dramatic increase in media and public attention to preprints [7]. As with any large-scale perturbation of a dynamic system, the results of this change are complex and difficult to derive.

Global understanding of and reaction to COVID-19 evolved markedly over a single year [8]. The COVID-19 coronavirus first surfaced in December 2019, in Wuhan. On December 31 the Chinese government confirmed that dozens of cases were being treated; and days later researchers had identified a novel virus. A month later, amid the reports of thousands of cases in China, the World Health Organization (WHO) -- based on early estimates of the disease's transmission and mortality rate -- declared a global health emergency. Six weeks later, countries outside China began substantial mitigation protocols, starting with travel restrictions. By December 2020, vaccines were developed, tested, approved, and disseminated [9].

In the 10 months between WHO's emergency declaration and the release of effective vaccines, 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 WHO and major governments for being slow to implement adequate public health measures, these scientific developments occurred at unprecedented speed [10]. In contrast, our understanding of how scientific research and scientific communication changed during the same period appears deficient. While scientists and scientific publishers clearly recognized the sudden urgency of communicating new research, and many initiatives were announced and promoted to accelerate scientific communication, we have learned relatively little about how much science and communication systematically changed, in what ways, and for what reasons. Why did the world learn so much more about COVID itself, and so little about how to share and evaluate scientific knowledge about it effectively -- and what can be done to increase the capacity for scientific communication to progressively improve?

Progress in understanding and mitigating COVID-19 relied on a scientific and empirical foundation that include systematic theory that describes the causal dynamics of global health at the systems level -- and which is specific enough to yield clear empirical implications that can be tested; standards, processes, and infrastructure to measure and compare outcomes of interest -- along with 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 currently lacks these features.

We describe how a systems approach can help identify and anticipate the consequences of changes to scholarly communication, using the article-processing charge model (APCs) and preprints as cases to explore a range of intended and unintended consequences. By anticipating the types of potential consequences in advance, and designing assessments with them in mind, those who would introduce interventions into the system may increase the chance they will succeed -- and learn whether they do. We start with an example from public health to highlight ways that complex systems resist reliable inferences and blunt ad-hoc interventions.

We focus on the use of preprints in the context of the COVID-19 pandemic and its attendant controversy, because the scale of preprints implies a major change in how scientific scholarly communication works, at least partly in response to the pandemic. In 2020, there were approximately 320,000 preprints posted, across arXiv, bioRxiv, medRxiv, OSF Preprints, PsyArXiv, SocArXiv, and additional services indexed by Europe PMC, an increase of 49% from the previous year. Relative to the number of articles listed in Web of Science, preprints have risen from 9% in 2019 to 14% in 2021, the greatest one-year increase since bioRxiv came online in 2013.[1] In comparison, APC open access publishing represents a larger share of scholarly publishing, having reached 26% of articles in Journal Citation Reports journals by 2019 [11]. Clearly, both preprints and APCs -- both relatively recent 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. However, we lack the information necessary to develop a thorough understanding of the effects of this change in the mechanism of publishing scientific results.

3 LEARNING FROM PUBLIC HEALTH INTERVENTIONS INTO SYSTEMS

The history of public health, as in science generally, is replete with cautionary examples, including cases in which selecting an intervention to pursue is difficult because the same pattern may result from very different mechanisms; 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. In scholarly communication the lack of clearly articulated goals and assessment targets threatens to create similar problems. To illustrate these challenges, we turn to the literature on public health, which shows a long history of complex systems posing challenges for measurement and generalization.

The use of household dichlorodiphenyltrichloroethane (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 vast reductions in relevant mosquito populations and in subsequent malaria cases and deaths, with beneficial economic effects [12]. However, DDT would later emerge as a paradigmatic case of unintended consequences for public health interventions. 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 [13]. 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 [14,15]. And, of course, there were the human health effects of DDT, and its effects on species up the food chain from its intended targets [16,17]. 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 [18].

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

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[1] We add arXiv submissions from https://arxiv.org/stats/monthly_submissions to preprints listed by Europe PMC at https://europepmc.org/Preprints. The Web of Science count reflects all articles listed for each year. The 2021 estimate is through October 26.

desired outcomes (shown in green): mosquito use and malaria reduction within targeted areas. Measuring these outcomes showed the intervention to be highly successful.

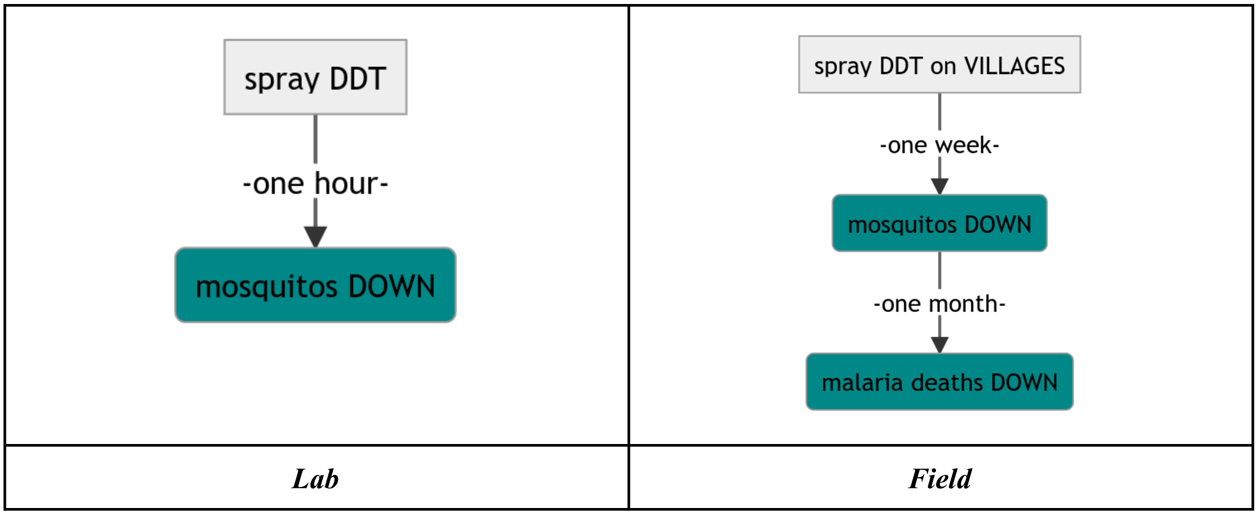

Figure 1. Measured local effects of DDT administration.

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 [17]. 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 [12].

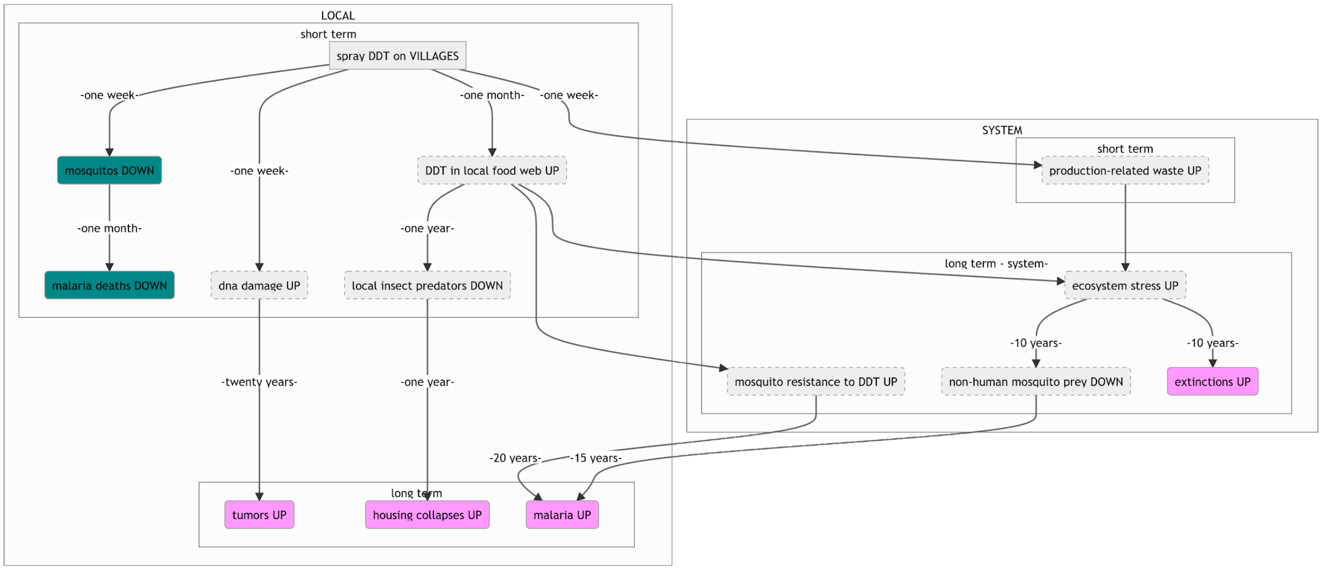

Figure 2: Measured and unmeasured effects of local DDT application. [2]

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 [19], in recent years have been widely used for fishing, with detrimental effects on local fish habitats through the capture of juvenile fish and other species [20].
- 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 [21].
- Vehicle safety innovations (anti-lock brakes, bicycle helmets, seatbelts), or preventive health measures since the 1980s (condom use, antiviral medication) might have encouraged more reckless behavior by altering risk profiles [22–24].
- Some abuses of trust by institutional actors, such as in the infamous Tuskegee Study (in which African American men were denied medical care to study the long-term effects of syphilis, from 1932 to 1972) create long term damage, in this case reducing doctor visits by African American men [25].

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. A key lesson to be drawn from the history of DDT and other public health interventions is: effecting durable and important changes in complex systems is rarely

[2] Note: Use this plugin to edit the graph: https://workspace.google.com/marketplace/app/mermaid/636321283856

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 development of innovations to anticipate potential threats and plan to assess a diverse set of intervention outcomes. We categorize these into four threats, each representing a targeted outcome for intervention, and the potential for unanticipated real-world effects.

- *Unobserved outcomes*. Regardless of the nature of a system intervention, unobserved events pose a set of unknown risks to inference. Assessing only the events immediately proximate to the intervention -- or those events intended to be affected (such as the number of people who use a service, or the market share of a product) -- without a process to detect other types of adverse events, has the potential to hide even local and short-term indirect costs. This leaves the researcher biased towards pronouncing the success of the intervention.
- *Unmeasured characteristics*. Closely related is the problem of narrow measure of the intended outcome and unspecified aspects of the treatment. An intervention may improve measured outcome even as it worsens unmeasured aspects -- undetected, if the assessment fails to embrace a holistic perspective. For example, a treatment that yields a positive outcome when applied by one set of practitioners may have negative effects when applied by others.
- *Ignored system*. 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 repels other actors, and it may alter contextual features of the system in ways that change common understandings. As Figure 1 illustrates, systemic effects may be temporally distant from the initial intervention.
- *Unknown causal 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 justify 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.

4 INTERVENTIONS IN THE SCHOLARLY ECOSYSTEM

4.1 Previous Interventions: APCs

The scholarly communication ecosystem is a complex human system, and interventions into it are affected by the threats we describe above. This is illustrated by the surprising consequences that emerged from a previous major intervention in health and medical publishing -- the launch of PLOS and the introduction of the megajournal model -- which popularized open access publishing funded by article processing charges (APCs). At the time of its launch in 2003, the first PLOS journal (PLOS Biology) charged an APC of $1500, which was "less than 1 percent of the cost of conducting the research itself," according to the organization [26]. APC-based open access publishing has steadily gained market share in academic journals, with payments increasingly being bundled into large contracts between universities or research funders and publishers. 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 [27]. However, among other possible unintended consequences, the cost of APCs has risen dramatically for high-prestige journals (especially hybrid journals that unlock individual articles for a price), contributing to economic inequality in author access to top-tier publications; and an industry of low-quality publisher has adopted the business model as well, extracting profits from poorer institutions and authors. Figure 3 illustrates selected spillover effects of this launch, using the same causal graph notation as above.

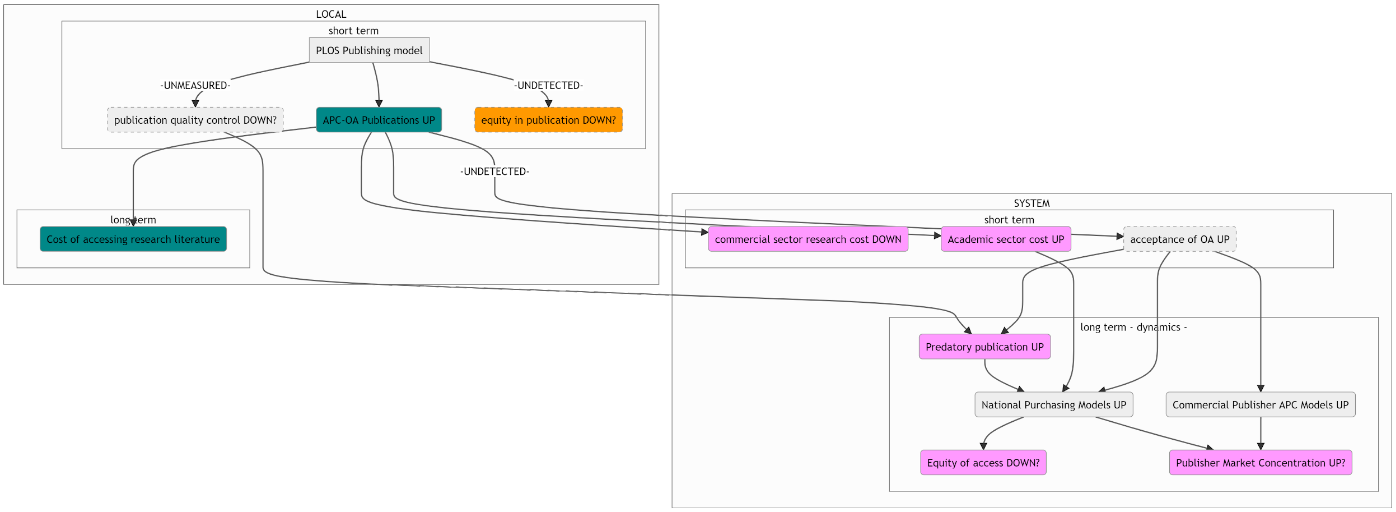

Figure 3: Some Unexpected Effects of Articles Processing Charges

As illustrated in the figure, the introduction of APC's had many consequences that were unanticipated because of unobserved outcomes, unmeasured characteristics, systemic effects, and long-run dynamics.

- *Unobserved events*. PLOS's success initially was evaluated primarily through the measurement of publications and submission. This is natural, as publication is desired and visible -- but leaves researchers choices not to publish unobserved. This blind spot underlies concerns that the APC model could deter scientists with less resources (particularly in the global south) from publishing their research -- independent of the research's scientific merit [28]. This threat to equity in science is further exacerbated by incomplete measures -- as the diversity of even published authors has not been systematically measured and evaluated.
- *Incomplete measurement*. 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, determining the effects of the APC model on quality is further complicated by the fact that the PLOS combines the use of APCs with explicit changes to the review process -- both in the selection of editors and the criteria used -- emphasizing technical correctness rather than merit. This dynamic can lead to quality censoring (decreased ability to measure quality through review and publication) and raises concerns that the quality of published scientific information is affected [22].
- *Systemic 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 organizations). 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 [23,29] Further, this shift in costs affects long-run dynamics by creating incentives for large research organizations or consortia to bargain for collective APC licensing [30].

- *Long-run dynamics*. It is possible that the increasing acceptance of APC publishing, combined with opacity in assessment of review quality, made predatory publishing models profitable [24]. 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 [30] -- and scholarly publishing has continued to its trend of commercial consolidation and concentration over this period. In the long runk, comprehensive licensing agreements between large research organizations and commercial publishers -- which lower the costs to both read and publish for those inside the agreements -- raise further equity concerns for independent researchers, those at poorer institutions, and those in the global south. [31,32]

4.2 Current Preprint Interventions

Using an ecosystem perspective, and from the public health and scholarly communication examples above, what can be learned from the introduction of preprints into the system of scholarly communication, and especially in the COVID-19 pandemic? By some interpretations, the pandemic has marked a turning point in the history of scientific publishing [31]. 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" [32]. Other journals accelerated publication, and made their COVID-19 content free, while many joined prominent research funders in calling for increased use of preprints as well as data sharing and transparency [33]. Suddenly it seemed the long standing arguments for preprints (and open access) had increased resonance. 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 [34], and PeerJ Preprints had only recently launched in the biological, medical, and environmental sciences [35]. bioRxiv differed from prior projects in a variety of ways: it was more selective; operated by a highly-respected, non-profit press; 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 [36]. At present there are more than 40 preprint servers that host medical and biomedical content [37], and many others outside the life sciences.

Today, bioRxiv is widely considered a resounding success [38] with policy changes by funders and universities having created incentives to post preprints [39], and the growth of new submissions following a geometric pattern [40]. Journals prohibiting the posting of preprints in the basic life sciences are now few and far between [41], 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, and will publicly post its peer reviewer reports as reviews of the preprints [42]. 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 [43]. 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, suggesting preprints were being used to disseminate findings at an earlier stage in response to the crisis [6]. 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, which implies that preprints reduced the time from discovery to reporting of results [44].

A significant factor promoting early sharing is the potential for increased 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 [45] and tweeted almost 20,000 times (according to Altmetrics). It was published in the journal *Indoor Air* more than six months later [46], but by then it had already played a key role in shifting public understanding of how the virus is transmitted [47]. 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 would have been saved by implementing interventions one or two weeks earlier [48]. 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 [49], 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) [50]. On the other hand, in a dramatic example of negative feedback having a salutary effect, a preprint claiming to find "uncanny similarity" between SARS-CoV-2 and HIV, posted to bioRxiv on January 31, 2020, was withdrawn two days later after other scientists immediately discovered errors in its analysis [51].

Such visibility can have positive consequences, such as garnering early recognition in the form of grants, jobs, and collaborations. Preprinting is associated with an increase in both Altmetric Attention Scores and citations [52,53]. 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.

While many servers subject preprints to screening before posting, this process is much less selective than the peer review conducted by most journals. 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 [54]. 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 [55]. 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).

4.3 Potential Unanticipated effects of preprints

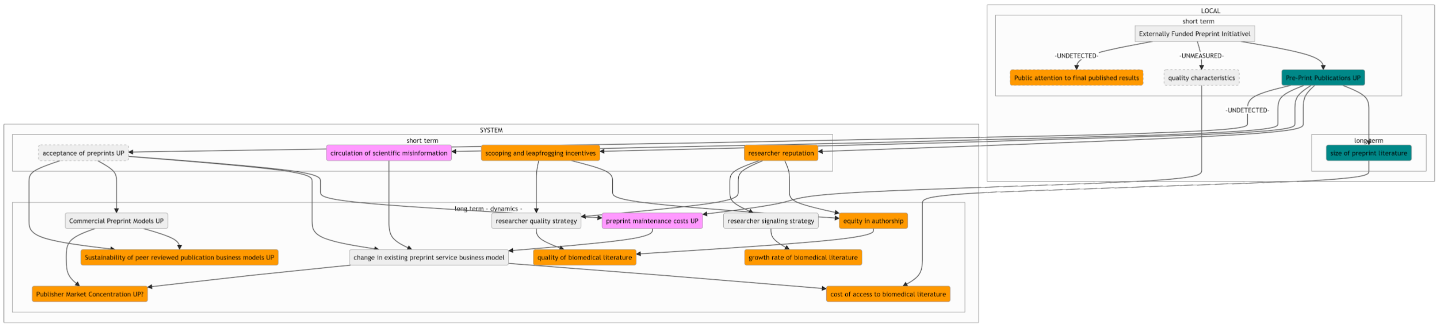

Figure 4: Potential Unanticipated Effects of Preprint Services

As the use of preprints has mushroomed, especially within the life sciences, both before and during the COVID-19 pandemic, a wide range of concerns and problems have been raised, by critics with a variety of interests and perspectives [56]. 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 partial solution to the problem of paywalled access to journal publications, by serving free copies of manuscripts, usually in an early version. To take advantage of this feature, the founders of bioRxiv have argued that research funders should implement a so-called Plan U (for "universal"), mandating preprints as an alternative to requiring final papers be published in open access journals [57]. However, this raises the possibility on an *unobserved outcome*, that readers who rely on preprints because they're freely available won't read subsequent, presumably improved versions that are behind paywalls (what publishers call the "version of record"), reinforcing a knowledge gap between those who have access to paywalled journal articles and those who do not (albeit a smaller gap than exists when preprints are not posted at all).

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 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 -- would affect our evaluation of the impact of preprints on the system overall, but we have no mechanism for gathering and analyzing this systematically.

Assessing the quality of preprints, and their potential systemic impact on the quality of published science, is made difficult by the fact that they represent a new form of science communication. We do not yet have established metrics for evaluating preprints, representing 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 be an indicator of success in identifying errors and problems early in the publication process, or a failure for 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 relevant 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, by alerting competitors to the presence of the work and inducing them to submit to a journal. Less-established researchers may be concerned that the act of preprinting could leave them vulnerable to being scooped, especially by better-resourced labs that can progress more quickly through the necessary experiments [58]. Many journals (including Nature journals [59]) do not consider a pre-existing preprint as a "prior publication," which may mean they do not establish precedence, which would 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. Well-established investigators may use perprints to garner visibility as a result of their name recognition, while junior scholars' preprints remain undiscovered [60]. 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 [61]. Cell Press offers authors Sneak Peek, which, while not using the term "preprint," is described as an, "author opt-in preview of the papers under review in our primary research journals" [62]. Another is Sage Advance, a "preprints community" for social sciences and humanities, which attempts to capture papers for submission to Sage journals [63]. 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 [56]. Thus, the disruption of the current publishing model may not work in favor of preprints, which raises the possibility that preprints will strengthen rather than weaken the hold of these publishers over the system of scholarly communication.

In addition to the possibility that bioRxiv may disrupt the business model of publishers (which many see as a feature, not a bug), there is concern that it will damage the embargo system that regulates scientific journalism. Embargoes are possible when journals control the timing of publication. They allow journalists time to prepare articles before a scientific paper is released, protecting them from being scooped by any competitor's article. In a preprint model, whoever first finds a preprint can report on it, and reporters may be incentivized to cut corners in order to get a story out faster. Critics worry that this system will generate a race to the bottom in science journalism [64].

Preprints may change the way researchers publish their work in unpredictable ways with consequences at the system level. For example, they may publish more low-quality work without fear of peer review, or use preprints to game citation metrics. They may publish work tactically to mark territory or intimidate less prominent scholars. If the release of a preprint by a well-funded lab discourages less-resourced competitors from beginning or continuing work in an area [65], the benefit to science of early reporting might be outweighed by the suppression of new ideas.

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 implies massive success, but if there are unanticipated systemic consequences, that assessment would be misguided. Critics already complain that disseminating research without prior peer review threatens public health [66], 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. So the scale of what they want to know is somewhere in between the immediate effects of their own intervention and the universe of possible system effects. Funders of particular interventions may not choose to support assessments of possible effects that are too far removed from an individual project, but the research community has an interest in wider understanding. This will require community-based assessments that different members can draw on to study the impact that various projects are having. That may also mitigate the problem of self-interested assessments, and allow the documentation of failures (for example, after the staff of an experimental project is let go).

Analyses of scholarly communication have generated calls for systemic reforms [67,68]. However, like biological ecosystems, scientific scholarly communication is a complex system 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, for the most part, through the efforts of individual communities and stakeholders to make science more open, transparent, and reliable. Thus, most 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* [69,70], which we label "Do It Now, Check Sometime" (DOINCS).

Under favorable conditions, DOINCS 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 may not generalize, and are potentially misleading. And evolving projects -- in which leaders and staff anticipate and respond to evolving developments -- do not always present ideal conditions for systematic assessment.

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: https://connect.biorxiv.org/relate/content/181). At first it was a simple list of related papers. However, on or before April 18, 2020 when the collection had 1940 articles, they added a disclaimer at the top of the page: "bioRxiv is receiving many new papers on coronavirus SARS-CoV-2. A reminder: these are preliminary reports that have not been peer-reviewed. They should not be regarded as conclusive, guide clinical practice/health-related behavior, or be reported in news media as established information." Then, on or before June 17, 2021, by which point the collection had blossomed to 16,772 articles, the wording of the disclaimer was changed to “formally peer-reviewed,” removing reference to “clinical practice,” and replacing “established information” with “conclusive.” The operators of the system were reacting to and anticipating the changing impact of preprints in a rapidly evolving crisis -- including rapid growth in attention to impactful preprints. However, it might be complicated to assess whether the attached disclaimer had its intended effects as the wording changed. 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 [71], combining a publishing innovation with an expert intervention into the evolving literature.

These are the kinds of 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 with a new form of disseminating scientific papers, in which the perceptions of reliability and peer review around preprints are being closely scrutinized. Without design principles in place to capture and assess data from an evolving intervention the opportunity for systematic analysis and understanding may be lost. In this case, fortunately, bioRxiv 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 [72], Altmetrics, and news media databases -- so it may be possible to study the effects of warnings and disclaimers on preprint reporting practices. However, to understand the full impact of preprints on 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 strongly suggests that conditions are generally not favorable to ad-hoc analysis. In general, effective interventions in complex ecosystems are built upon standardized systems-wide monitoring, explanatory theories that are sufficient to generate testable predictions about a range of proposed interventions, and interventions that are explicitly designed for causal evaluation.

5 DISCUSSION

The COVID-19 pandemic is a massive crisis that interrupted -- or overturned -- many aspects of science and social life simultaneously. Of course it is too soon to know its full effects. However, 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, preprints clearly have generated direct effects -- as can be measured by the growing proportions of scholars posting them, representing a growing share of all published scholarship -- but also indirect and unintended effects that we may never be able to systematically assess. Our conclusion from this review of the preprint experience in the light of the pandemic 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.

Naturally, the challenges illustrated by bioRxiv and medRxiv do not span the entire range of challenges that threaten reliable open science. To the contrary, generalizing from this case is easier than most because these platforms are highly visible, well-funded, and apparently successful. The majority of changes in science and publishing practice are probably smaller in scale, occur behind the scenes, and have less immediate and demonstrable effects. However, as the case study of preprints illustrates, even when there is general agreement that an open science intervention works -- for example, through exponential rates of 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 challenges to understanding we have sketched out here are endemic in science practice and scholarly communication. Moreover, as the history of public health and ecology makes clear, until the mechanisms of open science practice are understood, society will remain vulnerable to unwanted and potentially severe systems effects.

We agree that change is needed, and there are real costs to inaction. Scholarly communication in science is too slow [58], too expensive [73], and dominated by the concerns of powerful actors in wealthy industrialized nations [74]. In addition, problems of trust undermine public confidence in science, which is increasingly a partisan issue [75]. 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, even as it threatened public budgets [76]. 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.

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7 COMPETING INTERESTS

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