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ARTICLE

The Open Innovation in Science research field: a collaborative conceptualisation approach

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ABSTRACT

Openness and collaboration in scientific research are attracting increasing attention from scholars and practitioners alike. However, a common understanding of these phenomena is hindered by disciplinary boundaries and disconnected research streams. We link dispersed knowledge on Open Innovation, Open Science, and related concepts such as Responsible Research and Innovation by proposing a unifying Open Innovation in Science (OIS) Research Framework. This framework captures the antecedents, contingencies, and consequences of open and collaborative practices along the entire process of generating and disseminating scientific insights and translating them into innovation. Moreover, it elucidates individual-, team-, organisation-, field-, and society-level factors shaping OIS practices. To conceptualise the framework, we employed a collaborative approach involving 47 scholars from multiple disciplines, highlighting both tensions and commonalities between existing approaches. The OIS Research Framework thus serves as a basis for future research, informs policy discussions, and provides guidance to scientists and practitioners.

KEYWORDS

Open Innovation in Science; openness; collaboration in science; Open Science; interdisciplinary research

1. Introduction

The purpose of scientific research is to produce reliable knowledge and work towards understanding and solving societal, technical, and environmental challenges (Stokes 2011; Bush 1945). As these problems increase in complexity, they demand more creative solutions, highlighting the need for open and collaborative practices that involve non-scientific actors such as citizens, companies, and policymakers, as well as scientists from a range of institutions and disciplinary backgrounds (Jones, Wuchty, and Uzzi 2008; Van Noorden 2015; Ledford 2015).

More efficient and effective ways to foster openness and collaboration in science have long been discussed. Anticipated in early work by critics demanding a more 'social orientation of science' (Schroyer 1984, 715), new context-driven modes of knowledge production have developed that are centrally concerned with solving societal problems and are therefore more likely to transgress traditional disciplinary boundaries or distinctions between academic and applied research (Gibbons et al. 1994). Taking stock of these shifts, Dasgupta and David (1994) formulated a 'new economics of science', today one of the cornerstones of our understanding of the mechanisms of scientific openness and collaboration. However, changing conditions both within science (e.g. increased competition for permanent positions, increased specialisation, the globalisation of the scientific workforce) and outside of it (e.g. professionalisation of non-scientific actors, calls for public engagement and the democratisation of science, policy-driven agenda setting, global crises such as the COVID-19 outbreak) require a novel approach to thinking about the antecedents, contingencies, and consequences of openness and collaboration in science in a more integrated way.

One domain in which these issues are being worked out by researchers and practitioners alike is that of *Open Science (OS)*. OS can be understood as an umbrella term encompassing a variety of assumptions about knowledge production and dissemination (Fecher et al. 2017). The three pillars of OS are accessibility (e.g. open access to publications and research data), transparency (e.g. reproducibility of results, open peer review), and inclusivity (e.g. citizen science) (Vicente-Sáez and Martínez-Fuentes 2018). While the first and most broadly accepted two focus on access to existing scientific outputs and processes, only the third envisions opening up the knowledge production process itself.

Even as members of many scientific communities have promoted public participation in science to varying degrees (Lengwiler 2008; Strasser et al. 2019), the core processes of scientific discovery generally remain closed to outsiders. This feature of scientific knowledge production has received comparatively little attention within the OS research field. However, open and collaborative approaches at earlier stages of the scientific research process are increasingly being discussed, suggesting an evolution and expansion of OS priorities (Beck et al. 2019; Chan et al. 2019; Hossain, Dwivedi, and Rana 2016; Nature editorial 2018; Woelfle, Olliaro, and Todd 2011).

Another domain of research and practice focused on openness and collaboration in knowledge production is that of *Open Innovation (OI)*. Originally discussed in the context of changing research and development strategies at private-sector firms (Chesbrough 2003), OI has since been defined more generally as a distributed innovation process based on purposively managed knowledge flows across organisational and sectoral boundaries using pecuniary or nonpecuniary mechanisms (Bogers et al. 2017). OI entails a paradigm shift towards open and collaborative processes that increasingly displace and compete with producer-driven innovation, through practices that can take place outside (Baldwin and Von Hippel 2011) and between organisational boundaries (Chesbrough and Bogers 2014). OI practices embrace different inbound, outbound, and coupled processes for facilitating knowledge flows across boundaries with the purpose of generating innovations. Such practices include, but are not limited to, co-creating innovation between firms, lead users and user innovation communities, open-source software/hardware development, crowdsourcing and crowdfunding, patenting and licencing, or R&D collaborations (Dahlander and Gann 2010; Grimpe and Kaiser 2010; Jeppesen and Frederiksen 2006; Laursen and Salter 2006; Lilien et al. 2002; Poetz and Schreier 2012; Von Hippel and Von Krogh 2003).

As a complement to the focus on later stages of the scientific research process in OS, OI emphasises processes and logics of exchange in the early and intermediary steps of knowledge production. Of late, OI-influenced researchers have specifically explored these dynamics in the context of science (Beck et al. 2020; Franzoni and Sauermann 2014; Guinan, Boudreau, and Lakhani 2013; Lifshitz-Assaf 2018), extending the linkages between OI and the science context beyond different forms of technology transfer (Chesbrough 2020; Egelie et al. 2019; Perkmann et al. 2013). However, despite potential synergies between the OS and OI approaches, our understanding of open and collaborative practices in the science context and their related antecedents, consequences, and contingencies remains limited and fragmented. In part, this is because activity is scattered across many different domains of research and practice. On the scholarly side, OS and OI are investigated using different disciplinary lenses, from sociology (e.g. Moore 2018) and economics (e.g. Maniadis and Tufano 2017) to management (e.g. Alexander, Miller, and Fielding 2015) and policy (e.g. Bogers, Chesbrough, and Moedas 2018). On the applied side, various OS or OI initiatives are currently being implemented and facilitated by scientists, firms, policymakers, and funding agencies. However, these initiatives are labelled with a dizzying array of terms such as *academic entrepreneurship, citizen science, inter- and transdisciplinary research, public engagement, responsible research and innovation, technology transfer*, or *third mission activities*.

We argue that placing these concepts into relation helps us to form a more comprehensive picture of the various factors shaping open and collaborative practices in science. More specifically, we suggest that bringing together the complementary concepts of Open Science and Open Innovation makes it possible to examine specific exchange relationships and translation services between science and other sectors of society. To better integrate these concepts, we propose the concept of *Open Innovation in Science (OIS)* as a unifying foundation for advancing our understanding of antecedents, contingencies, and consequences related to applying open and collaborative research practices along the entire process of generating and disseminating new scientific insights and translating them into innovation. We define OIS as a process of purposively enabling, initiating, and managing inbound, outbound, and coupled knowledge flows and (inter/transdisciplinary[1]) collaboration across organisational and disciplinary boundaries and along all stages of the scientific research process, from the formulation of research questions and the obtainment of funding or development of methods (i.e. conceptualisation) to data collection, data processing, and data analyses (exploration and/or testing) and the dissemination of results through writing, translation into innovation, or other forms of codifying scientific insight (i.e. documentation) (see Figure 1).

To tackle the challenge of mapping this expansive research field, we took a multi-step collaborative approach involving 47 scholars from the social sciences, humanities, and natural sciences. Together, we worked to 1) jointly conceptualise the OIS Research Framework; 2) map relevant literature streams defining the different elements, logics, and interdependencies to be synthesised; and 3) write this article (see Appendix A for an overview of the entire process and a reflection on the benefits and difficulties of using a collaborative approach).

As the principal output of this process, our article contributes to science, policymaking, practice, and society in at least three ways. First, employing an open and collaborative approach allowed us to bridge disciplinary differences in terms of underlying norms, theories, assumptions, methods, and languages. This interdisciplinary approach made it possible to synthesise what dispersed fields within the scientific community already know about open and collaborative research practices. Second, integrating different perspectives provided a more comprehensive picture that identifies robust results but also contradictions, tensions, and inconsistencies across scientific fields. These highlight the need for methodologically diverse inquiry to better understand the antecedents, boundary conditions, and consequences of open and collaborative research. Third, structuring the knowledge about open and collaborative research

[1]While various definitions of inter- and transdisciplinary research refer to different constitutive elements (e.g. on the level of knowledge integration, see Piaget 1972), we refer to interdisciplinary research in terms of crossing boundaries of existing scientific disciplines and transdisciplinary research in terms of crossing the boundaries of the science system to involve actors other than academic scientists such as citizens, companies, and policymakers.

practices that we synthesised in terms of multi-level antecedents and contingencies, as well as outcomes and impacts, provides a common foundation for jointly developing a future research agenda. In particular, the cross-level interdependencies between these constructs promise to yield valuable insights for the pursuit of purposefully opening the scientific research process and for a growing body of scholarship on the science of science (Brown, Deletic, and Wong 2015; Fortunato et al. 2018; Wuchty, Jones, and Uzzi 2007).

In what follows, we introduce the OIS Research Framework and provide an overview of OIS practices (section 2.1.), multi-level antecedents to and contingencies for successfully implementing OIS practices (section 2.2.), and (intermediary) outcomes, as well as scientific and societal impacts of applying OIS practices (section 2.3.). In section 3, we outline major contributions from synthesising cross-disciplinary knowledge about open and collaborative scientific practices. Several areas for future research are then presented in section 4, before conclusions are offered in section 5.

2. Conceptualising the Open Innovation in Science (OIS) research field

To return to the definition provided above, OIS is a process of purposively enabling, initiating, and managing knowledge flows and (inter/transdisciplinary) collaboration across organisational and disciplinary boundaries in scientific research. Thus, the OIS Research Framework comprises three main elements with recurring interrelations (see Figure 1). First, *OIS practices* occur at all stages of the scientific research process, from the formulation of research questions and the obtainment of funding and the development of methods (i.e. conceptualisation) to data collection, data processing, and data analyses (i.e. exploration and/or testing), as well as the dissemination of results through writing, translation into innovation or other forms of codifying scientific insight (documentation). Second, whether and under which circumstances these OIS practices can be successfully applied is influenced by *contingencies and boundary conditions* on multiple levels (i.e. individual, research team or group, organisation, discipline or field, and society or policy levels). These factors (considered independently and in combination) influence the application of OIS practices, as well as the outcomes and impacts they generate. We emphasise that it is important to take a balanced view that recognises contingency factors: we do not see openness and collaboration as ends in themselves, but as potentially powerful means for improving the novelty, efficiency, and societal impact of scientific research. However, the effectiveness of these approaches depends on the types of factors noted, such that open and collaborative approaches may not be suitable for every scientific undertaking. Third, *OIS-based outcomes* can ensue along the entire scientific research process (e.g. proposals, datasets, protocols, code, publications, patents, teaching materials, science-based innovations). These outcomes may have *scientific and societal impacts*, such as an accelerated response to novel diseases.[2] Those impacts also

[2]For example, consider the role of open and collaborative practices in responding to the COVID-19 pandemic. A groundswell of scientific knowledge-sharing across disciplinary, organisational, and national boundaries allowed for rapid and coordinated progress to be made (Apuzzo and Kirkpatrick 2020). Preprint servers like bioRxiv and medRxiv allowed researchers to report and evaluate findings quickly, while more than thirty scientific publishers agreed to make selected publications openly accessible for the duration of the crisis. And while do-it-yourself efforts to address shortages of medical devices and supplies were stymied at times by a lack of understanding of clinical needs (Zastrow 2020), these efforts to 'hack the crisis' also revealed societal reserves of insight and generosity that the science system has yet to fully tap.

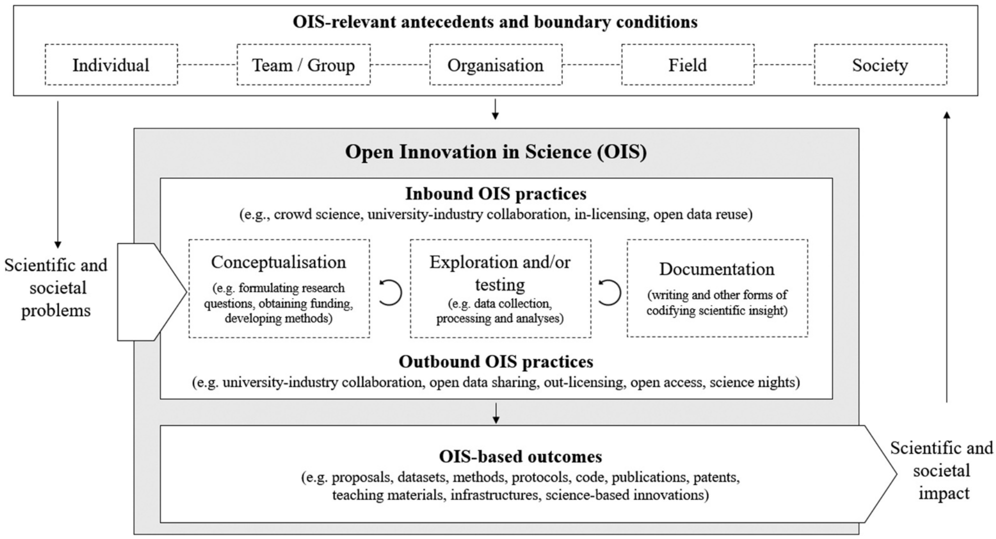

Figure 1. The OIS research framework. Note: 1) OIS is embedded in the wider context of science, including problems, antecedents and boundary conditions, and scientific and societal impacts. 2) OIS approaches scientific knowledge production and dissemination as an iterative process, meaning that scientific and societal impacts feed back into problems as well as antecedents and boundary conditions.

include the identification of under-researched scientific and societal problems that are subsequently prioritised, thus feeding back to the starting point of scientific research.

In what follows, we discuss each of these elements of the OIS Research Framework, moving from OIS practices (section 2.1.) and antecedents and boundary conditions (section 2.2.) to OIS-based outcomes and impacts (section 2.3.). In presenting a synthesis of available knowledge on open and collaborative research practices across different disciplines in the social sciences, humanities, and natural sciences, we do not claim exhaustiveness, but rather focus on the big picture, identifying interdependencies between elements, as well as tensions and incongruities that point to future research directions.

2.1. OIS practices and methods along the entire scientific research and dissemination process

OIS practices can be applied across the entire scientific research process. They may involve a) academic scientists only, or b) actors without formal scientific training, such as citizens, companies, or policymakers, as well as scientific actors working outside of academia[3]. In what follows, we use this distinction to offer a taxonomy of OIS practices, their characteristic elements, and examples of how they are used. This overview is not

[3]We distinguish between scientists whose primary place of employment is an academic research organisation (i.e. universities and research institutes) and scientists who are independent or employed at other organisations including government agencies, non-profits, and companies with primarily commercial interests. We specifically do not make this distinction with respect to the value or quality of the scientific knowledge produced. However, we see it as relevant in the context of OIS, as academic and non-academic actors may be influenced by different institutional logics (e.g. importance of scientific publications for career advancement) that influence their decision-making and, in turn, their open and collaborative behaviour (Sauermann and Stephan 2013).

exhaustive and the practices presented may have secondary applications involving other sets of actors, but our aim in this section is to define exemplary categories of OIS practices.

2.1.1. OIS practices involving academic scientists only

OIS practices that exclusively involve academic scientists include collaborations across disciplinary and organisational boundaries (e.g. interdisciplinary, 'big', or distributed collaborations), as well as inbound and outbound knowledge flows such as data- and material-sharing and open access publishing.

2.1.1.1. (Inter)disciplinary collaborations. The boundaries of discipline-based research are blurring, with important research questions lying at the intersection of traditional disciplines (Nowotny, Scott, and Gibbons 2006). Interdisciplinary research has been defined as 'a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialised knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or area of research practice' (National Academy of Sciences, National Academy of Engineering, and Institute of Medicine 2005, 2). The degree of knowledge integration from source disciplines varies from borrowing and contrasting to integrating and transcending existing bodies of knowledge (Miller 1982). Rafols and Meyer (2010) thus prefer to describe interdisciplinarity in terms of diversity and coherence, highlighting the breadth and novelty of knowledge integration. It can be difficult to establish when interdisciplinarity takes place, as cognitive overlaps make boundaries between and within disciplines difficult to identify. Thus, a more fine-grained classification for levels of interaction, for example from weak to full, may be suitable (Huutoniemi et al. 2010).

2.1.1.2. Shared scientific infrastructure. A special case of interdisciplinary collaboration are large-scale research infrastructures that provide scientists access to highly specialised instrumentation and experimental conditions beyond the reach of most research organisations. Experiments at such facilities require collaboration between permanent scientists and external users (Hallonsten 2016). This can range from short-lived interactions to highly complementary collaborations in which local instrument scientists and visiting scientist-users bring together needed expertise and skills (D'Ippolito and Rüling 2019). In this context, a culture of openness can emerge, with norms governing the allocation of credit for the resulting output. Long-term collaborations also help to advance the development of instruments themselves (Tuertscher, Garud, and Kumaraswamy 2014), facilitating interdisciplinary collaboration between actors who might not otherwise collaborate (Kaplan, Milde, and Cowan 2017). Prominent examples of large-scale or 'big science' collaborations include the Manhattan Project, the Human Genome Project, and the Large Hadron Collider experiments at the European Organisation for Nuclear Research (CERN). Such a shared infrastructure can facilitate or even necessitate the application of OIS practices.

Increasingly, virtual and remote labs (formerly known as 'collaboratories') also make it possible for scientists who are not physically on site to control instruments and monitor data remotely (Bos et al. 2007; Teasley and Wolinsky 2001). This setup carries advantages for science education (Heradio et al. 2016; Waldrop 2013) and permits a more efficient use of expensive instruments (Finholt 2002; Heck et al. 2018; Kraut, Egido, and Galegher 1988). Among space physicists, for example, relaxing the requirement to travel to remote observatory sites has expanded the number of potential participants in research tasks such as data collection. This arrangement has been shown to make participants more diverse in terms of experience and expertise (Finholt 2002).

2.1.1.3. Data and materials sharing. Another form that (interdisciplinary) scientific collaboration takes is the sharing of intermediate research products. The ability to build on existing knowledge depends on access not only to published findings, but also to underlying data and materials such as cells and cultures used in prior research (e.g. Andreoli-Versbach and Mueller-Langer 2014; Czarnitzki, Grimpe, and Pellens 2015; Furman and Stern 2011; Mokyr 2002). Data sharing is thus an essential backstop for the scientific principles of credibility and replication, allowing researchers to build more quickly on prior work and allowing data sharers to achieve more visibility and impact (Beck et al. 2019; Chan et al. 2019; Hossain, Dwivedi, and Rana 2016; Nature editorial 2018; Woelfle, Olliaro, and Todd 2011; Czarnitzki, Grimpe, and Pellens 2015; Borgman 2015). There are two primary paths for data sharing: voluntary data sharing via private communication and public repositories (e.g. archives, federated data networks, virtual observatories), and mandatory data disclosure in response to policies by journals (Rousi and Laakso 2020) and funders (Andreoli-Versbach and Mueller-Langer 2014). Costs for preparing research data to be reused are high, limiting sharing behaviour even among advocates (Fecher et al. 2017; Plantin 2019). These costs, including time to format, annotate, and curate the data, as well as concerns over privacy, 'scooping', and misuse, must be balanced against the promised efficiencies of data reuse (Pronk 2019). One way to reduce these costs is by (real-time) storing and sharing of certain kinds of data automatically, without the need for human intervention (Rouder 2016). Another relates to the model of data science as a service (Grossman et al. 2016; Mishra, Schofield, and Bubela 2016), in which scientists upload their data to cloud-based service providers that may also offer some level of processing and analysis. Meanwhile, innovations like the open materials transfer agreement developed by the BioBricks Foundation are providing legal frameworks for research organisations to share biological materials on an open basis.

2.1.1.4. Open publishing. Open flows of knowledge between academic scientists can also be observed at the later stages of the research process, such as the dissemination of research results on an open access basis. Open access is defined as 'mak[ing] research literature available online without price barriers and without most permission barriers' (Suber 2012, 8). Distinctions are made between 'gold' and 'green' routes to open access: the former refers to research outputs that are freely available at the point of publication, while the latter refers to semi-final versions made available by scientists themselves via repositories and preprint servers like arXiv (European Commision 2020). A recent large-scale analysis found that at least 28% of research literature is available via these mechanisms (Piwowar et al. 2018). Meanwhile, sites like SciHub illicitly provide access to even broader swathes of publications (Himmelstein et al. 2018). Key debates around open access hinge on the role of incumbent commercial publishers, with new actors from library publishers to funders vying to disrupt what has been termed an 'oligopoly' (Larivière, Haustein, and Mongeon 2015) with the help of open-source publishing tools and platforms (Maxwell et al. 2019). Concerns over existing quality assurance mechanisms have also given rise to a range of innovations in peer review, from publishing and/or deanonymising review reports to crowdsourcing reviews (Ross-Hellauer 2017).

2.1.2. OIS practices with actors other than academic scientists involved

Academic engagement has been defined as 'knowledge-related collaboration between academic researchers and non-academic organisations' (Perkmann et al. 2013). It represents an important way to transfer scientific research beyond academic boundaries and to gain novel insights. In this section, we discuss the role of actors other than academic scientists (e.g. representatives of the public, industry, and politics) in the scientific research process.

2.1.2.1. The general public as co-creator in the scientific research process. Historically, the public understanding of science (Durant, Evans, and Thomas 1989) considered scientists as bearers of knowledge and 'lay' citizens as recipients of a scientific education. More recently, a more democratised model has emerged, in which the public is engaged with science in a variety of ways. For example, in medicine, deeper interactions between scientists and patients have increased the motivation of scientists to engage in innovation activities (Llopis and D'Este 2016). Today, members of the public can co-create and disseminate scientific research through practices such as citizen science or crowd science. Although these practices are marked by some particularities (e.g. level and stage of engagement), they have many similar elements (e.g. sourcing external knowledge). Both can be considered promising approaches to organising science in that they increase the scope of problems under investigation and multiply types of potential participants.

While citizen science is not yet defined in a unified way (Eitzel et al. 2017; Heigl et al. 2019), the term is frequently used in reference to the engagement of volunteers (who may not be academics or may be academic scientists in other fields) who collect or analyse data in scientific projects (Silvertown 2009). More generally, *crowd science* involves 'scientific research done in an open and collaborative fashion' (Franzoni and Sauermann 2014, 1). Some studies have categorised citizen and crowd science projects based on the degree of participant involvement (Shirk et al. 2012; Wiggins and Crowston 2011). Most of these frameworks place a co-created approach as the highest level, emphasising the democratisation of science by bridging the gap between academia and the public (Bonney et al. 2009). At this level, the most widely recognised practices are associated with community-based activism (English, Richardson, and Garzón-Galvis 2018). Research questions emerge from community concerns, findings inform government policies, and scientists assist the public with tools to conduct an experiment or collect measurements (English, Richardson, and Garzón-Galvis 2018; Scheliga et al. 2018). New approaches include providing citizen scientists with remote access to laboratory instruments (Heck et al. 2018) and offering co-authorship (Vaish et al. 2017), as well as gamified approaches that attempt to sustain participants' motivation (Tinati et al. 2017). These strategies promise to catalyse creativity and out-of-the-box thinking, leading to different and potentially more valuable scientific outcomes (Anderson 1994;

Bergen 2009; Tsai 2012). The path towards co-created interactions is particularly challenging for highly mathematically oriented optimisation projects such as Foldit (Cooper et al. 2010) and Quantum Moves 2 (Jensen et al. 2020), which deal with core challenges that are quite disconnected from everyday knowledge. For such computational citizen science projects (Rafner et al. 2019), educational efforts and increased emphasis on the design of the interface may be necessary to create meaningful interactions.

Benefits from citizen science projects are manifold and accrue to academia, the individual (citizen) scientists, and society at large. For example, such projects can generate new domain-specific knowledge and innovations (e.g. Hecker et al. 2018), critical insight into how humans solve problems individually and collectively as compared to machines (Heck et al. 2018), and unique learning opportunities for citizens (Shah and Mody 2014). While citizen science holds promise for human-machine integration, we are just beginning to understand, for example, difficulties arising from designing human-machine systems for serendipitous discovery (Trouille, Lintott, and Fortson 2019).

A particular strength of citizen and crowd science is their potential to draw on larger bases of contributors, expand areas of scientific inquiry, and arrive at results more efficiently. To this end, both citizen science and crowd science may use *crowdsourcing* techniques to organise scientific projects. Crowdsourcing is defined as 'the act of outsourcing a task to a "crowd" rather than to a designated "agent" (an organisation, informal or formal team, or individual) such as a contractor, in the form of an open call' (Afuah and Tucci 2012, 355). Since it can be difficult to know *ex ante* who is best able to solve problems, broadcasting them to a large and open crowd invites problem-solvers to self-select into participation (Lakhani et al. 2007; Tucci, Afuah, and Viscusi 2018). However, citizen and crowd science are OIS practices that have mostly been used for producing scientific inputs (e.g. collecting or coding data). Dissemination efforts, in contrast, have remained mostly unidirectional, with the exception of science nights or fairs that can be described as interactive science communication events (Bultitude, McDonald, and Custead 2011). Such events can be quite diverse in terms of their duration, location, and organisational backing. Relatedly, if less richly interactional, (micro)blogging platforms like Twitter allow (lay) actors to communicate publicly with scientists about their research findings, thus helping to shape perceptions of the disseminated content (Puschmann 2014).

Increasingly, both citizen and crowd science are moving beyond contributory involvement to become more co-created (Majchrzak and Malhotra 2020). Members of the public are getting involved at the later stages of the scientific research process, such as critically reflecting on the potential consequences of particular research findings and co-developing a suitable dissemination strategy to avoid misunderstandings while initiating informed debates (e.g. Ganna et al. 2019). At the same time, the responsible research and innovation movement has emphasised the involvement of citizens before research projects even begin, through processes of priority setting and anticipatory governance. This approach comes with a responsibility for all involved stakeholders to become mutually responsive and to consider the societal implications of research and innovation activities (e.g. European Commision 2013; Owen, Macnaghten, and Stilgoe 2012).

2.1.2.2. Industry actors as co-creators in the scientific research process. While the commercialisation of scientific knowledge can be undertaken by academic scientists themselves (e.g. through science-based start-ups), much market-oriented knowledge transfer involves partnering with industry actors to co-create and apply scientific research. These OIS practices vary in terms of the level of interaction with existing industry actors. For example, while spinouts and patenting or licencing activities typically require lower levels of engagement, university-industry collaborations can cover the entire spectrum from contributory to co-creative interactions (Perkmann et al. 2013).

The numbers of patents filed and spinout companies formed have become key indicators of university impact on industry and society (D'Este and Perkmann 2011), even though this impact appears to be primarily generated through other, less visible mechanisms such as contract research, consulting, and staff mobility (D'Este and Patel 2007; Perkmann et al. 2013; Perkmann and Walsh 2008). Patenting entails the creation of a legal framework whereby 'the patented invention can normally only be exploited [...] with the authorisation of the owner of the patent' (World Intellectual Property Organization 2004). Giving such an authorisation to another actor, usually in exchange for money, constitutes a licencing process. There has been a dramatic increase in the number of patents taken out by academic scientists and research organisations (Lissoni et al. 2008). However, the effectiveness of university patenting and licencing as a vehicle for technology transfer is influenced by other, more informal mechanisms such as direct interactions. Openness, seen here as the leakage of knowledge, can also impede patentability because of the novelty requirement embedded in the patenting process (Pénin and Burger-Helmchen 2011).

Spinouts are 'companies founded by an academic inventor aiming to exploit technological knowledge that originated within a university to develop products or services' (Bigliardi, Galati, and Verbano 2013). Spinouts are popular among policymakers, due to the belief that they are effective vehicles for advancing the industrial application of scientific knowledge and, simultaneously, creating jobs and growth (e.g. Carayannis et al. 1998; Druilhe and Garnsey 2003; Rasmussen and Wright 2015). Nonetheless, studies show that spinouts are highly prone to failure, have little impact on local or regional economic development (Mustar, Wright, and Clarysse 2008), and grow less than other high-tech companies (Ensley and Hmieleski 2005). As a result, many research organisations have shifted their focus from maximising the number of created spinouts to strengthening potential value creation and emphasising their own role in research dissemination (Jacob, Lundqvist, and Hellsmark 2003; Moray and Clarysse 2005; Wright et al. 2006).

Collaborative ties between universities and industry can also take the form of long-term relationships that make use of multiple mechanisms for knowledge exchange. These are usually built on (and reinforce) strong personal and informal relations between individuals (e.g. Cohen, Nelson, and Walsh 2002; Feller and Feldman 2010; Grimpe and Fier 2010). Direct collaboration can stimulate 'bench-level' relationships between individual researchers and industry partners, and thus help to foster mutually meaningful exchanges (e.g. in the form of learning or access to in-kind resources) (D'Este and Perkmann 2011). In addition, contract research and consulting can help to build trust among collaborators (Cohen, Nelson, and Walsh 2002; Perkmann and Walsh 2008) and pave the way for new and long-term ventures.

While OIS distinguishes between academic and non-academic scientists on the basis of different ideal-typical institutional logics (e.g. in terms of workplace characteristics, worker characteristics, the nature of the work, and the disclosure of results), there is also substantial variance within academia and industry, respectively (Lam 2010; Sauermann and Stephan 2013). Hence, collaborations among academic or non-academic scientists can be as varies as those between academic and non-academic scientists, highlighting the importance of context and of individual characteristics. Industrial scientists may be similar to academic scientists in terms of their shared understanding of particular scientific topics and norms, but differ with respect to individual-level preferences for factors such as pay, autonomy, or openness (Roach and Sauermann 2010).

There are also significant interdependencies between practices that connect academic scientists to industry, implying that it does not make sense to champion one practice as inherently preferable. Boosting university-industry interaction requires a range of approaches that grow out of underlying personal ties (Feller and Feldman 2010; Olmos-Peñuela, Benneworth, and Castro-Martínez 2016; Perkmann et al. 2015). For instance, commercialisation will often be an outcome of or a follow-on activity to collaboration between academic scientists and industry actors, rather than a stand-alone activity (e.g. Lawson 2013).

2.1.2.3. Policymakers as co-creators in the scientific research process. Besides the public and industry actors, policymakers at various levels of government also collaborate with scientists. Traditionally, the engagement of policymakers in scientific research has been defined by the setting of science and innovation policies. Government institutions directly fund research and are thus inevitably involved in influencing research directions (Gläser and Laudel 2016). In defining research policies, policymakers are charged with interpreting the priorities of a variety of stakeholders in the relevant polity, including citizens, industry actors, other government agencies, and scientists themselves. Although the steering of science along these lines is significant, its impact on research is mediated in various ways. These steering actions are generally either conducted through funding schemes, on which scientists in different fields may depend more or less heavily, or through requirements for educational institutions, which are increasingly managed by professional administrators and have policy agendas of their own (Huisman and Seeber 2019). Of course, scientists themselves also play a role in influencing the form these steering actions take.

Recently, though, the adoption of mission-oriented approaches to science and innovation policy has required policymakers to engage more intensely with scientific research (Borrás and Edler 2014; Kuhlmann and Rip 2018; Mazzucato 2018). Missions have a much more focused scope than the traditional programme areas of research funders. They focus the attention of scientific communities on so-called grand challenges (e.g. plastic-free oceans instead of sustainability). These challenges are not scientific as such, but address societal needs. To be implemented effectively, these policy agendas need to influence and be influenced by a greater variety of stakeholders, including scientists.

Finally, policymakers are becoming active co-creators of scientific research through open and collaborative policymaking practices. Open government data often provides the foundation for these practices, giving a wider range of stakeholders the ability to assess and build on public-sector initiatives (Attard et al. 2015). A more ambitious step involves setting up policy labs where scientists, policymakers, and other stakeholders collaboratively participate in foresight and scenario-building exercises, thus co-advancing science and innovation. Examples include the IdeaLab in Denmark, Sitra in Finland, Vinnova in Sweden, and the EU Policy Lab of the European Commission.

2.2. Antecedents and boundary conditions for applying OIS practices along the entire scientific research and dissemination process

Whether and when OIS practices can be applied and how they affect the outcomes and impacts of scientific research depends on numerous antecedents (i.e. drivers and barriers) and boundary conditions (i.e. contingencies). These help to determine how best to manage inbound and outbound knowledge flows and (inter-/transdisciplinary) collaboration along the entire process of generating and disseminating scientific research. In this section, we highlight such factors at different levels of analysis: 1) the individual level; 2) the research group or team level; 3) the (research) organisation level; 4) the discipline or field level; and 5) the society or policy level. However, there are also dynamics that cut across the different levels.

2.2.1. Individual-level antecedents and boundary conditions

First, we introduce individual-level antecedents and boundary conditions for applying OIS practices. The individual level comprises all 'human factors' related to individual persons, including attitudes, capabilities, skills, and prior experiences. Research has suggested that individual-level factors may be more important than organisation-level characteristics in studying openness and collaboration in science (Perkmann et al. 2013). The rationale for this is that universities can be described as professional bureaucracies (Mintzberg 1993) whose members largely decide which activities to participate in (D'Este and Perkmann 2011). While research and teaching activities are mandatory for most academic scientists, industry- and impact-oriented activities are typically optional and a matter of personal choice (Azagra-Caro 2007; Lee 2000; Thursby and Thursby 2004). Even as these expectations begin to shift, whether scientists are able and willing to apply open and collaborative practices is likely to be influenced directly or indirectly by their individual-level factors.

2.2.1.1. Scientists' individual background and characteristics. Beyond personal choice, scientists' education and prior experience appear to influence the application of OIS practices like founding science-based start-ups. For example, company founders with a PhD are more likely to adopt Open Science strategies (Ding 2011). Unsurprisingly, researchers who have entrepreneurial experience are more likely to start a new firm (Abreu and Grinevich 2013; Shane and Khurana 2003). Similarly, researchers with an interdisciplinary career trajectory and work experience in industry are likely to have higher patent productivity (Abreu and Grinevich 2013; Dietz and Bozeman 2005). Scientists are also more likely to have entrepreneurial intentions if they have a more diverse and balanced skill set, but only if they are in contact with entrepreneurial peers (Lazear 2004; Moog et al. 2015). Another characteristic identified as a driver of open and collaborative behaviour is individuallevel absorptive capacity – that is, the ability to recognise, absorb, assimilate, and apply new knowledge (Cohen and Levinthal 1990). However, there may also be selection bias in these findings, with scientists moving to research organisations and contexts that are more welcoming of open and collaborative practices.

Other studies have suggested a relationship between personality traits (e.g. the Big Five) and certain aspects of or drivers for sharing behaviour such as creativity or information seeking (Batey and Furnham 2006; Heinström 2003; Linek et al. 2017). Moreover, personal characteristics such as gender and age may influence the application of OIS practices. Several studies suggest that older and male researchers are more likely to engage in open and collaborative practices (e.g. Ding and Choi 2011; Link, Siegel, and Bozeman 2017; Tartari and Salter 2015). Possible reasons for this finding include differences in available time, industry experience, risk affinity, career pressure for young scientists, network size, and environmental and institutional support (Abreu and Grinevich 2013; Burns, O'Connor, and Stocklmayer 2003; Ding, Murray, and Stuart 2006; Stephan and El-Ganainy 2007). Gender differences in collaboration activity can, however, be tempered by contextual factors, such as the presence of other women in the work environment and institutional support for the careers of female scientists (Tartari and Salter 2015). Elsewhere, it has also been argued that age is inversely related to research productivity and the acceptance of new ideas, with older researchers tending to be less active, more sceptical about patenting, and more closed-minded (Davis, Larsen, and Lotz 2011; Stephan 1996).

Finally, the outsized influence of exceptional individuals needs to be mentioned. According to the so-called Matthew effect (Merton 1968), eminent scientists receive disproportionately greater credit for their work, while lesser-known scientists receive disproportionately lesser credit for similar contributions to science. Eminent scientists are also likely to attract disproportionately greater amounts of resources such as funding, which may give them better opportunities to engage in resource-intensive OIS practices. Research on the 'star scientist' effect (Zucker, Darby, and Armstrong 2002) has shown that some scientists exhibit both superior scientific and entrepreneurial performance, thus playing a key role in the advancement and commercialisation of science.

2.2.1.2. Scientists' attitudes, identities, and motivations to share knowledge. Scientists' attitudes, identities, and motivations, in conjunction with descriptive norms and perceived behavioural control, seem to predict intentions to engage actively with the public (Poliakoff and Webb 2007) and share research data (Kim and Adler 2015) more reliably than institutional factors such as support measures, education, or training (Guerrero, Urbano, and Fayolle 2016). For example, patenting activity has been shown to depend strongly on individual scientists' perception of the costs and benefits of patenting and, thus, their willingness to disclose inventions (Baldini, Grimaldi, and Sobrero 2007; Bercovitz and Feldman 2008; Haeussler and Colyvas 2011; Lam 2011; Owen-Smith and Powell 2001; Tartari and Breschi 2012).

Commercialisation propensity is influenced by scientists' belief that knowledge dissemination is a crucial mission for universities (Renault 2006), perceived support from the research organisation (Moutinho et al. 2007), and beliefs about the (positive) personal and professional outcomes of patenting (Owen-Smith and Powell 2001). In this sense, the conventional assumption that scientists' research activities are motivated by intrinsic satisfaction and reputational rewards, while their commercial activities are driven by the desire for financial gain, may reflect an oversimplified view of human motivation (Lam 2015). Rather, scientists are driven by a wide variety of motivational factors, including the desires to produce new knowledge, solve a particular problem, and transform their discoveries into societal impact (Bammer 2008; Cohen, Sauermann, and Stephan 2020; Huutoniemi et al. 2010; Lam 2011; Siedlok, Hibbert, and Beech 2014).

The professional identity of academic scientists has been a sustained object of research (e.g. Henkel 2005), and has recently been shown to play a critical role in the ability to adopt and even initiate open and collaborative practices. For example, scientists at the National Aeronautics and Space Administration (NASA) who perceived themselves as experts in their field experienced a crisis of their identity as heroic innovators and problem-solvers when experimenting with platform-based innovation challenges (Lifshitz-Assaf 2018). While some scientists were sceptical about working with non-experts, others were highly enthusiastic about the resulting breakthroughs. These scientists went through a process of transforming their identity to see themselves as solution-seekers instead of problem-solvers, thereby embracing open approaches. They were also found to have a more interdisciplinary career history, a factor that contributed to their ability to embrace such changes.

Finally, scientists' motivations play an important role in driving openness and knowledge-sharing. Motivations such as the desire to learn, reciprocity, signalling, or the pursuit of an exciting idea influence sharing behaviour (Lakhani and Wolf 2003). Scientists appear to be willing to share (prepublication) results in exchange for feedback and credit and as a means to attract collaborators (Thursby et al. 2018). They also express a growing willingness to share data, particularly if formal citation is ensured (Tenopir et al. 2020). However, these motivations also differ among scientists from different fields, given that 'decisions about the openness of materials involve ongoing assessment of value' (Levin and Leonelli 2017, 289). Indeed, one study suggests that 70% of field variation in disclosure is related to differences in respondents' beliefs about norms, competition, and commercialisation (Thursby et al. 2018; Haeussler et al. 2014). Particularly in fields with high mutual dependence, such as mathematics and physics, scientists disclose to attract new researchers to the field and to deter others from working on identical problems (Thursby et al. 2018).

2.2.2. Team- and group-level antecedents and boundary conditions

This section outlines some exemplary team- and group-level antecedents (i.e. drivers and barriers) and contingencies for (successfully) applying OIS mechanisms. These factors are grouped in terms of a) team or group composition and roles, and b) peer effects. While we acknowledge disciplinary differences around how social entities comprised of multiple researchers are described and organised (e.g. team, group, lab), we refer to *teams* as networks of individuals with a shared responsibility for performing interdependent tasks that have definite start and end points (i.e. when goals are achieved). Research *groups* are a more durable structure characterised by the leadership of a principal investigator, in which the group members' tasks can be independent from each other and training is often an important function.

2.2.2.1. Team or group composition. Individuals working together to create knowledge may be physically collocated, but they increasingly work in distributed ways and may not meet or interact in person regularly. This has the effect of increasing coordination and communication costs for the team or group (Hoegl, Weinkauf, and Gemuenden 2004). Key advantages of teamwork in science, however, include diversity, division of labour, and knowledge recombination (Bozeman and Youtie 2017; Horwitz and Horwitz 2007; Uzzi et al. 2013). A considerable body of research explores how the composition of a team or group and related factors around roles and role diversity influence open and collaborative behaviour (Somech and Drach-Zahavy 2013).

Team diversity seems to facilitate the application of OIS practices in several ways. Assembling people with different organisational roles or backgrounds, and who possess a range of skills, knowledge, and expertise, helps teams unravel complex tasks related to scientific knowledge production (Van Noorden 2015). Similarly, heterogeneous vocabularies, cognitive patterns, and styles can expose individuals to a greater variety of novel ideas and lead to knowledge recombination (Fleming and Sorenson 2004; Gruber, Harhoff, and Hoisl 2013). However, positive effects seem to diminish following an inverse-U shape with increasing cognitive distance (Wuyts et al. 2005). Recent research has set out to differentiate the effects of having individual team members with interdisciplinary backgrounds (intra-personal diversity) or team members who are specialists in different disciplines (inter-personal diversity) (Haeussler and Sauermann 2020).

Beyond the composition of a team or group, team size seems to matter (Curral et al. 2001), although contradictory findings point to unknown contingencies. While large teams have benefits in terms of labour inputs, knowledge diversity, and division of labour (Wuchty, Jones, and Uzzi 2007), they may struggle with becoming too unwieldy to enable effective exchange and engagement (Mote et al. 2016). Others have concluded that large teams tend to develop science and technology incrementally, while small teams tend to be more disruptive (Wu, Wang, and Evans 2019). One contingency that may moderate size effects is the team's integrative and absorptive capacity, which has been shown to be crucial for knowledge integration (Gruber, MacMillan, and Thompson 2013; Salazar et al. 2012).

Individual scientists' positions within a more hierarchically structured research group also influence participation in engagement and entrepreneurial activities. For instance, groups' principal investigators (PI) generally take a lead role in driving collaborations with industry, requiring them to be 'jacks of all trades'. In taking on the roles of project manager, negotiator, and resource acquirer, as well as that of researcher, PIs develop a set of competences and experiences that allow them to function as boundary spanners between academia and industry (Boehm and Hogan 2014). Yet they are also called upon to care for the careers and well-being of the graduate students and postdocs within their groups, even to the point of refusing discourses of responsible research and innovation in favour of a more localised sense of responsibility (Davies and Horst 2015). Such early-career researchers are increasingly engaging with industry in the context of projects funded through a PI that involve industry collaborators (Lee and Miozzo 2015; Thune 2010). But their structural position means that they also incur professional risks if they push for adopting open practices when a group leader does not favour them (Bahlai et al. 2019).

2.2.2.2. Peer effects. Individuals, the teams or groups they compose, and their performance are highly influenced by the attitudes and behaviours of their peers, as well as by prevailing local norms. These effects may also influence how individual actors perceive and engage with OIS. For example, when deciding to collaborate with industry or engage in patenting activities, academic scientists tend to mimic the behaviour of departmental colleagues at a similar stage in their careers (Moog et al. 2015; Tartari, Perkmann, and Salter 2014) and the prevailing department culture instead of taking their lead from university patenting policies (Bercovitz and Feldman 2008; Kenney and Goe 2004). While the presence of role models can positively affect academic scientists' propensity to engage in entrepreneurial activities (Huyghe and Knockaert 2015), such effects nevertheless remain variable, in part because individual scientists vary in the degree to which they are influenced by their peers. For example, early-career researchers are more influenced by the collaboration behaviour of peers in their immediate social environment (Tartari, Perkmann, and Salter 2014). Likewise, the industry involvement of younger scientists has been shown to increase with the industry orientation of local peers (Aschhoff and Grimpe 2014). However, this relationship may not hold for all forms of OIS.

2.2.3. Organisational-level antecedents and boundary conditions

Individual scientists and research teams or groups are usually embedded in larger research organisations, from universities and their subunits (i.e. departments) to more experimental multidisciplinary institutes (Mosey, Wright, and Clarysse 2012). Antecedents and boundary conditions at the organisational level can influence the (successful) application of OIS practices. Hence, there are organisational capabilities that influence the ability to adopt open and collaborative practices, such as absorptive capacity (Piezunka and Dahlander 2015), epistemic stance about the innovation process (Fayard, Gkeredakis, and Levina 2016), and frame flexibility (Raffaelli, Glynn, and Tushman 2019). In this section, further exemplary antecedents and contingencies are discussed, such as the infrastructures and incentive systems that foster open and collaborative practices among the scientists these organisations employ.

2.2.3.1. Organisational infrastructure. The infrastructures of research organisations, defined in terms of support services and technical systems that underpin core functions like research and teaching, can both support and hinder OIS activities. Over time, specialised infrastructures have evolved to act as agents in knowledge and technology transfer processes (Geuna and Muscio 2009). In particular, Technology Transfer Offices (TTOs) have attracted a great deal of attention in innovation studies. The TTO's role is, loosely, that of a boundary spanner or broker between academia and industry, helping academic scientists to understand the needs of industry and providing support for commercialisation activities, partner search and match, management of intellectual property, and new venture development (O'Kane et al. 2015; Siegel, Waldman, and Link 2003). While some studies indicate that TTOs play only a marginal and indirect role in driving academic researchers to enter into new ventures (Clarysse, Tartari, and Salter 2011), others indicate that these offices can promote industry orientation and third mission activities (Huyghe and Knockaert 2015). Researchers have found that TTOs may actually slow down rather than accelerate the transfer process, because they seek to safeguard the interests of the researchers and to maximise financial returns to the university (Franza, Grant, and Spivey 2012; Link, Siegel, and Bozeman 2017). It appears that the details of how a TTO is implemented matter more than the establishment of the form itself.

Moreover, internal policies and protocols can also be seen as organisational infrastructures intended to foster industry collaboration. For example, university-level patent regulations can signal organisational commitment to patenting activities (Baldini, Grimaldi, and Sobrero 2007). But official policies may also lead to symbolic rather than actual changes to behaviour: researchers may engage in superficial compliance with local policies regarding entrepreneurial behaviour, pretending to live up to expectations without actually reorienting their research (Bercovitz and Feldman 2008). Similarly, mechanisms to support spinout formation do not necessarily strengthen researchers' incentives to start a company (Fini, Grimaldi, and Sobrero 2009). More successful endeavours centre trust, communication, and the role of intermediaries to facilitate knowledge transfer and resolve barriers such as ambiguity and difficulties with knowledge absorption and application (de Wit-de Vries et al. 2019). One intriguing model initiated by CERN involved setting up business incubation centres in its sponsoring states to support entrepreneurs in taking CERN technologies and know-how to market.

Looking beyond infrastructures for commercialisation, library-managed institutional repositories have become one of the standard tools with which research organisations make it easier for scientists to share outputs. While early predictions of their transformative potential (e.g. Lynch 2003) proved overly optimistic, the passage of open access policies and the adoption of new service models have expanded researcher participation (Dubinsky 2014). More recently, research organisations have also sought to configure physical spaces like FabLabs to empower communities and work towards solving societal problems (Dorland, Clausen, and Jørgensen 2019). However, since these infrastructures are generally cost centres that do not directly produce revenue, their ongoing viability likely depends on a widely perceived alignment with organisational mission.

2.2.3.2. Multi-level incentive structures. Traditional academic reward systems fall short in incentivising the adoption of OIS practices. Academic scientists' performance evaluation at the organisational level (i.e. for hiring and promotion) is often strongly based on so-called high-impact publications and external grant awards. A narrow focus on these metrics has been shown to hinder scientists' engagement with open and collaborative practices such as publishing in novel open access outlets or engaging in third mission activities (Alperin et al. 2019; Brembs, Button, and Munafò 2013). Existing incentives also tend to foster individual autonomy through internal and external networking. More collectively oriented incentives may be required to motivate, mobilise, and direct the efforts needed to successfully implement open and collaborative approaches (Breunig, Aas, and Hydle 2014). These include the design of specific incentives for ensuring the reproducibility of results, which could benefit faster dissemination and iteration of scientific findings (Nielsen 2011; Nosek et al. 2015). Incentives for open and collaborative behaviour can take a range of forms. For example, some publications have found that researchers are more likely to share their research data when a badge indicating whether results have been reproduced or replicated is published along with their article (Kidwell et al. 2016), although the evidence here is mixed (Rowhani-Farid, Aldcroft, and Barnett

2020). Scientists are known to place a value on non-monetary rewards that increase their likelihood of succeeding in academia, and which help to validate their identity and to create societal impact (Beck et al. 2019).

Incentive structures beyond the organisational level also have ramifications for the decisions that research organisations make about investing in openness and collaboration. For instance, while interdisciplinary research has more difficulty attracting external funding (Bromham, Dinnage, and Hua 2016; Banal-Estañol, Macho-Stadler, and Pérez-Castrillo 2019) it also generates more citations (Larivière, Haustein, and Börner 2015) and confers institutional prestige (Torres-Olave et al. 2020), thus involving a high risk/ high reward trade-off for both academic scientists and organisations deciding whether to prioritise such research (Fortunato et al. 2018; Leahey, Beckman, and Stanko 2017). National and international rankings of research organisations tend to exert a conservative influence (Hazelkorn 2015; Husemann et al. 2017), focusing narrowly on traditional measures of research productivity – an ethos also known as 'publish or perish' (Hazelkorn 2015; Husemann et al. 2017) – and failing to account for other aspects of scientists' work, such as multidisciplinary engagement, data sharing, and novel forms of collaboration like citizen science. Even so, higher education systems like that in the Netherlands (VSNU et al. 2019) are pivoting towards a model of evaluating both individual scientists and their organisations with a greater diversity of measures, promoting the construction of 'portfolios of worth' (Rushforth, Franssen, and de Rijcke 2019) that include different types of scholarly activity. Similarly, guidelines for good scientific practice co-created by a group of Nobel Laureates propose to 'change the reward system' so as to promote scholars' investment in transparency, openness, and accessibility (Lindau Guidelines 2020). These developments illustrate the individual, organisational, and policy-level interdependencies around academic incentive structures, indicating that these are particularly crucial for the successful implementation of OIS practices.

2.2.4. Field-level antecedents and boundary conditions

OIS explicitly embraces scientific discipline or field as a level of analysis, that presents domain-specific attributes which may affect OIS practices and outcomes. In this section, exemplary antecedents and contingency factors for these effects are discussed, from a) disciplinary differences in terms of incentives and norms to b) the technologies used in particular fields and, increasingly, across them.

2.2.4.1. Disciplinary differences regarding OIS practices. While scholars have moved away from strongly essentialist approaches to conceptualising disciplines (Trowler 2014), these social formations continue to shape scientists' ways of working and thinking (Becher and Parry 2005; Leisyte and Dee 2012). This includes their outlook on specific OIS practices, as well as scientific openness and collaboration more generally. Some researchers have investigated the meanings and implications of openness for scholars in particular disciplines (Knöchelmann 2019; Levin and Leonelli 2017). Others have examined the relative likelihood of scientists in different fields to engage in particular practices.

For instance, studies of university-industry collaboration consistently reveal that fields including the applied sciences and parts of the social sciences, such as economics and management studies, are more prone to collaborations with the private sector, patenting, and spinout formation (e.g. Azagra-Caro, Carayol, and Llerena 2006; Bozeman 2000;

Powell, Koput, and Smith-Doerr 1996; Schartinger, Rammer, and Fröhlich 2006). Other field-specific factors that influence the adoption of open and collaborative practices relate to incentive structures (e.g. Leahey, Beckman, and Stanko 2017; Siedlok, Hibbert, and Beech 2014), the extent of collaboration (Lewis, Ross, and Holden 2012), and the opportunity costs of commercialisation (Cohen, Sauermann, and Stephan 2020).

Scholars have long seen the competing claims of their employing research organisations and their various disciplinary communities as one of the central tensions in academic science (e.g. Clark 1987). This dynamic also points to interdependencies between drivers and barriers of openness and collaboration in science at these different levels of analysis. For instance, discipline has been found to be a stronger predictor of faculty support for economic development and knowledge commercialisation efforts than organisational climate – an effect that is, however, moderated by individual ideological convictions (Goldstein, Bergman, and Maier 2013). Findings like this underscore the importance of a multi-level approach.

2.2.4.2. Technologies of openness and collaboration. Scholars of science have paid increasing attention to the role of specialised instruments in the production of scientific knowledge, many of which were developed in and became strongly associated with particular disciplinary communities (e.g. Lenoir and Lecuyer 1997). As interdisciplinary problems and research teams come to the fore, though, previously domainspecific technologies are being adopted by scientists across fields. This diffusion has facilitated the distributed application of OIS practices. For example, the now-widespread availability of 3D printing technology has paved the way for open-source hardware to be used as research equipment (Pearce 2012). The possibility of producing open-source hardware is lowering the bar for conducting experiments that, in the past, would have required the modification of commercially available equipment or expensive customised manufacturing. This proves particularly powerful in developing countries, where it can be difficult to obtain and maintain the high-tech equipment used in modern laboratories. In addition, 3D printing increases the reproducibility of experiments, because identical research equipment that has been validated by other scientists and openly licenced can be produced at different sites (Murillo et al. 2019). These new fabrication technologies have also accelerated the process of scientific and technological development (Wajcman 2015). In the hands of the citizen science and maker movements, these technologies are being incorporated into hackathons and makeathons that lower both the cost and the time needed to innovate (Lifshitz-Assaf, Lebovitz, and Zalmanson 2020).

Software developments have also facilitated the application of open and collaborative practices in science. The advent of dedicated platforms like InnoCentive have made it easier to decompose the scientific and technological development process into component tasks and accordingly, to distribute it among multiple actors and entities (Felin and Zenger 2014; Lakhani, Lifshitz-Assaf, and Tushman 2013). The free and open-source software movement provided inspiration to early calls for Open Science (Willinsky 2005), and today the transparency of open-source code allows the scientific community to cross boundaries around field-specific software packages and converge on common solutions like the software environment R. Another example is REANA, a research data analysis platform created by CERN to enable code and data reuse and reproduction, which has generated interest in disciplines well beyond physics (Pujol and Wareham

2019). However, as certain kinds of scientific research becomes inextricable from the software that supports them, software curation and preservation are becoming essential to secure the integrity of the scholarly record (Chassanoff and Altman 2020).

Moreover, the pervasiveness of everyday technologies and broad participation in social media can facilitate scientific dissemination and engagement with the public (Newman et al. 2012). While popular commercial applications such as Google's G Suite leave users little control over how to engage with them, purpose-built tools like SciNote (SciNote 2020), developed by ScienceAtHome, emulate elements of the process of scientific argumentation (Fischer et al. 2014) and allow users to collaboratively create, share, and evaluate each other's ideas. Finally, Wikipedia, the largest open collaborative knowledge effort, which was initially revolutionary and has become an everyday tool, has been an important model for self-organising Open Science communities (Arazy et al. 2016; Faraj, Jarvenpaa, and Majchrzak 2011).

2.2.5. Society and policy-level antecedents and boundary conditions

Developments in society, including but not limited to the policy landscape and the structures of government that underpin it, influence openness and collaboration in science, as the former comprise the context in which other levels of analysis are embedded. Societal issues, legislative measures, and regulatory frameworks may thereby act as antecedents and boundary conditions for OIS practices and outcomes.

Scholars have found evidence of constellations of social institutions and cultural values that facilitate or block openness in science (e.g. Godin and Gingras 2000; Sovacool 2010). Such analyses increasingly begin not from essentialist assumptions about national character, but from a political economy perspective that emphasises power and contingency (Tyfield et al. 2017). For example, the centrality of non-commercial open access publishing in Latin America can be explained, in part, by the historical lack of market penetration by commercial publishers in the region (Becerril-García et al. 2019). One contemporary issue that has gained widespread attention is that of public trust in science, although its relationship to openness and collaboration is a complex one. While the latter are often presented as remedies for a crisis of trust in science, low trust can also deter social actors from participating in the very forms of public engagement that are meant to enlist their support (e.g. Dawson 2018). This effect may be further compounded by what social scientists have framed as the active and strategic production of ignorance (Proctor and Schiebinger 2008).

Against the backdrop of these developments, policymakers have emphasised the need for closer ties between science and society (Conceição et al. 2020), at once legitimising the application of open and collaborative methods and embracing a logic of accountability that has exposed researchers to disabling cultures of audit (Shore 2008). For example, funding schemes have seen a shift from more flexible recurrent block funding towards project funding mechanisms that are associated with greater precarity for early-career researchers and, arguably, less innovative research (Franssen et al. 2018). This reflects a broader change in relations of authority over the governance of research priorities, as the increasing exogeneity, formalisation, and substantive nature of governance mechanisms – as well as the strength and extent of their enforcement – have reshuffled the relative authority of different social groups over the evaluation of research (Whitley 2011).

Other policy changes that have affected OIS practices include an emphasis on the transfer of university research to industry as a means of unlocking economic growth (e.g. Berman 2011; Etzkowitz and Leydesdorff 2000; Shane 2004). Perhaps the best-known legislative vehicle for this agenda was the Bayh-Dole Act, adopted in the United States in 1980. Before the Act's passage, inventions resulting from federal research funding were assigned to the federal government; after its passage, though, universities were permitted to retain ownership of an invention and, in the event of its commercialisation, the associated revenues (Stevens 2004). The consequences of this legislation included an increase in patenting and licencing activities at elite universities as well as at universities that were previously inactive in the area of knowledge transfer, while raising concerns about a shift away from basic research towards applied questions (Mowery et al. 2001). Parallel legislation adopted in Europe proved to be less effective. The main reasons were found to be lack of adequate internal support mechanisms, the often embryonic nature of technology transfer offices, and the absence of patenting incentives (Grimaldi et al. 2011). Thus, vesting ownership of inventions in universities is no longer considered optimal. Indeed, there is renewed interest in revisiting the system of 'professor's privilege' that these reforms were intended to replace (e.g. Ejermo and Toivanen 2018).

In Europe, there have also been calls for the development of a European-level research space, within which distinct rules of knowledge production, legitimacy, and use can be negotiated (Wedlin and Nedeva 2015). For example, to increase the reusability of research data that has been shared via repositories or other open mechanisms, leaders at the 2016 G20 Summit signed a document supporting the adoption of the 'FAIR Guiding Principles of Scientific Data Management and Stewardship' (Wilkinson et al. 2016), which were later formally endorsed by the European Commission. Political support for making research data across Europe findable, accessible, interoperable, and reusable (FAIR) was thus translated into technical specifications for metadata, approaches to identification and indexing, protocols for access, and appropriate attributes for identifying provenance. Further efforts to support data sharing and reuse include the European Open Science Cloud, an ambitious effort to connect national-level infrastructures in an effort to harmonise data management according to FAIR principles, and the COVID-19 Data Platform, launched in April 2020 to bring together relevant datasets and accelerate research responding to the coronavirus pandemic.

Another set of society-level factors affecting the application of OIS practices relates to what are considered valid reasons for limiting openness and collaboration. Here, too, the case of research data is instructive, as expectations for accessibility are now widely cast in terms of the dictum 'as open as possible and as closed as necessary'. Permissible reasons for not sharing data have been taken to include privacy concerns reflected in regulations like the General Data Protection Regulation (GDPR), security considerations, and protection for commercial or industrial exploitation. Issues of social justice also demand to be considered as boundary conditions, as with the growing movement for indigenous data sovereignty (Kukutai and Taylor 2016). In these cases, research suggests that mediated revelation to selected actors via trusted intermediary organisations can help to mitigate the risks of complete openness (e.g. Perkmann and Schildt 2015).

2.3. OIS-based outcomes along the entire scientific research and dissemination process and potential scientific and societal impacts

This section focuses on the outcomes, as well as the scientific and societal impacts, of open and collaborative practices along the entire process of generating and disseminating scientific research. Outcomes, here, are not restricted to finished products; they include intellectual or material products and activities at earlier stages of the research process as well as tacit outcomes that are harder to codify. Scientific and societal impacts refer to the consequences of the knowledge produced through the application of open and collaborative practices, as it is taken up, in the science system and in other sectors of society, respectively.

2.3.1. (Intermediary) outcomes of OIS practices along the entire scientific research and dissemination process

The outcomes of applying OIS practices can be located in traditional scientific outputs such as peer-reviewed publications, as well as in a range of other knowledge objects not previously considered research outputs in their own right. The growing prevalence of open and collaborative practices thus exposes the limits of traditional scientometrics, with its focus on citation counts and networks (Mingers and Leydesdorff 2015). Defining and tracking these new outputs, assessing their quality, and allowing their creators to capture value from them, pose significant challenges (Beck et al. 2019; Bornmann 2013). While efforts to track and codify more diverse scientific activities are underway (e.g. pre-registration platforms, peer review crediting schemes like Publons), open and collaborative practices are rarely, if ever, rewarded. Likewise, when relational outcomes are considered, they are often limited to training and sustaining narrow research communities rather than encompassing the formation of dialogic relationships across disciplines and sectors of society (Phillips 2011).

Outcomes of OIS practices can be seen prior to the initiation of any particular research project, with the involvement of citizens and other stakeholders in priority setting (e.g. Manafò et al. 2018). Such processes can result in modified funding calls, evaluation guidelines, or, in rare cases, even a decision not to pursue a given line of inquiry: consider the bans at various levels of governance on human cloning research, some of which were informed by processes of public consultation. These outcomes, in turn, can feed into the composition of diverse research teams and the co-development of research proposals that, in both substance and format, differ from those initiated by scientists alone (Williams et al. 2010). Even as elements of research design like the selection of methods can be considered outcomes of collaboration, open lab notebooks and platforms like protocols.io also facilitate the sharing of research instruments and tacit knowledge about their use. Depending on the project, this might include technical artefacts like code or fully functioning tools that others can adopt for their own purposes. Beyond the sharing of data, open and collaborative practices at earlier stages of the research process can then result in the iterative development of ‘thinking infrastructures’ (Bowker et al. 2019).

Outcomes of open and collaborative practices at the later stages of the research process can closely resemble those of research that does not apply OIS practices. For instance, a scientist could write a standard article for a traditional journal and then arrange to have it published open access, gaining a citation advantage in the process

(Evans and Reimer 2009). Other familiar outputs at this stage include patent applications and various types of one-way science communication (Davies 2008). But documentation and dissemination of research findings can also take more innovative forms, as with interactive digital scholarship in the humanities and social sciences that is starting to challenge the dominance of outputs like the article or monograph even as it draws researchers into new kinds of collaboration (Nowviskie 2011). Inviting collaborators to define relevant outputs for their communities can reduce the need for a subsequent process of research translation, even as it places demands on scientists to master new genres. In some cases, scientists may also take an active role in transforming research findings into product, service, or social innovations, whether in their role as an employee of a research organisation or by taking up a new role outside of the academic science system (e.g. Fritsch and Krabel 2012). These activities can also be understood as outcomes of openness and collaboration in science.

2.3.2. Scientific and societal impact of OIS practices along the entire scientific research and dissemination process

Efforts to open scientific research processes are not an end in themselves, but an important means of producing more impactful scientific research. Thus, as outcomes of OIS practices ensue along the entire research and dissemination process, they can create scientific and societal impacts along the way. We distinguish impacts from outcomes or outputs, understood as concrete intellectual or material products and activities, by highlighting both planned and unforeseen consequences of the uptake of these products and activities within the science system or in other sectors of society (Penfield et al. 2014).

2.3.2.1. Scientific impact. While OIS may influence the science system and its stakeholders in a number of ways, here we highlight impacts associated with increased novelty, reliability, and efficiency in scientific practices. Research has shown that novel combinations of knowledge from diverse sets of actors can lead to more impactful ideas (Uzzi et al. 2013). Thus, one type of impact related to the application of open and collaborative practices in science is catalysing novelty. As we have seen, boundary-crossing inputs at the early stages of the research process can help to identify new and relevant scientific problems (Beck et al. 2020; Sauermann et al. 2020). Breakthroughs during the exploration and testing phases of scientific research have been linked to the application of OIS practices in a variety of scientific fields, including heliophysics (Lifshitz-Assaf 2018), radiation therapy (Mak et al. 2019), and bioinformatics (Blasco et al. 2019). Open and collaborative dissemination practices have also been tied to increased novelty, as with the uptake of scientific knowledge from sources like Wikipedia into original research agendas (Thompson and Hanley 2018).

Another type of impact stemming from the application of OIS practices relates to the reliability of scientific knowledge. The sharing of research data and protocols has led some fields to diagnose and begin responding to a so-called replication crisis (Open Science Collaboration 2015). Even in fields where replication may not be valued or possible, parallel logics of transparency and reflexivity are being articulated in terms of local cultures of evidence (e.g. Elman, Kapiszewski, and Lupia 2018).

Yet we should not assume that the impacts of applying open and collaborative practices in science are unambiguously positive. For instance, the practice of pre-registering hypotheses and/or research designs stands to increase reliability by distinguishing between tested and retroactive predictions (known as 'p-hacking' when used to cherry-pick statistically significant effects) that may gloss over negative results (Nosek et al. 2018; Yamada 2018). However, research on innovation contests shows that making ideas public at an early stage risks generating many similar ideas and stifling creativity (Wooten and Ulrich 2015). Likewise, increased team sizes may promote novelty through knowledge recombination, but 'too collaborative behaviours' may also distort team dynamics leading to citation farming and other forms of research misconduct (Seeber et al. 2019; Walsh, Lee, and Tang 2019). In the realm of scientific publishing, the article processing charge (APC) model of open access has opened the door to so-called predatory journals, which imitate legitimate titles but fail to provide a thorough review process. Researchers may unwittingly submit to journals like these without verifying their reputability or even do so strategically in pursuit of an easy publication (Dobusch and Heimstädt 2019; Sorokowski et al. 2017). Negative impacts like these are not necessarily inherent to openness and collaboration, but reflect interdependencies with other aspects of the science system that demand to be addressed.

In sum, while open and collaborative practices in science can impose constraints and introduce distortions, the disruptions that these practices involve can also foster creativity and renewal from the inside (Frankenhuis and Nettle 2018). In the short term, these developments may well be more time- and resource-intensive. But in the long run, they promise efficiencies in terms of reducing unnecessary duplication and allowing scientists to address new problems by 'standing on the shoulders of a taller giant' (Arza and Fressoli 2017, 465). Thus, gaining a better understanding of mechanisms that facilitate openness and collaboration in science can optimise the application of OIS practices, unlocking these system-level efficiencies and clearing a path for more impactful research.

2.3.2.2. Societal impact. Outcomes of OIS practices along the entire research process can also create societal impact, often understood in terms of social, cultural, environmental, and economic returns (Bornmann 2013). Scholarship on the societal impact of science has traditionally focused on economic impact, and evidence does suggest that open access to research findings and data can lead to savings in labour and transaction costs, as well as enable new products, services, and collaborations (Fell 2019). For example, open and collaborative practices of scientists have allowed drug development companies to become more profitable by avoiding parallel investments (Altshuler et al. 2010; Chaguturu 2014; Priego, Pujol, and Wareham 2019) and identify new market opportunities (Gruber, MacMillan, and Thompson 2008; Rothaermel and Boeker 2008). Defining the needs of prospective customers is a major step in the commercialisation of any new technology, and a given technology may meet customer needs in multiple domains but generate greater value in one or another (Bresnahan and Trajtenberg 1995). Open and collaborative practices can thus help academic entrepreneurs to understand the opportunity landscape by sourcing information from external actors, including crowds (Gruber, MacMillan, and Thompson 2013). This search for solutions has been compared to searching on a 'rugged' landscape (Kauffman and Levin 1987; Levinthal 1997), in that members of a crowd will be situated across the entire spectrum of search space and therefore have access to distant knowledge not held by the initiating actor (Afuah and Tucci 2012). Thus, economic impacts can result from both inbound and outbound processes of knowledge transfer in the context of OIS.

Recent work on societal impact has emphasised the previously underestimated contributions of the social sciences and humanities (Muhonen, Benneworth, and Olmos-Peñuela 2020) and the need to account for not only positive, but also negative impacts of developments in science (Derrick et al. 2018). For example, the creation of new markets in connection with Open Science may allow ‘platform capitalists’ to capture value from scientific knowledge without creating significant value for the science system (Mirowski 2018), a circumstance which highlights the importance of suitable appropriation strategies. A renewed interest in non-economic forms of societal impact and in valid indicators of these impacts (e.g. Tahamtan and Bornmann 2020) can also be seen. Familiar forms include scientific policy advice that leads to changes in policies or administrative practices (Kropp and Wagner 2010). Distinctive forms of impact linked to the application of open and collaborative practices include the identification of relevant societal problems as priorities for scientific research through methods like crowdsourcing (e.g. Beck et al. 2020; Lifshitz-Assaf 2018). Here, research is guided towards socially relevant problems, while the legitimacy of the scientific enterprise and public accountability are reinforced in the form of a ‘new social contract’ for science (Simon et al. 2019). Likewise, hybrid forums of experts and citizens can contribute to ‘the democratization of democracy’ (Callon, Lascoumes, and Barthe 2009, 225) by bringing together different forms of knowledge needed to identify and prioritise societal problems.

The impact of engaging the public in science was long understood in terms of helping citizens develop a better understanding of scientific practices (Trumbull et al. 2000) and achieving greater scientific literacy (Miller 1998). Yet the dominance of this framing has since been called into question (e.g. Stilgoe, Lock, and Wilsdon 2014). Recent work on ‘extreme’ or co-created citizen science still confirms this educational dimension of citizen participation (English, Richardson, and Garzón-Galvis 2018; Suess-Reyes et al. 2020). But more dialogic and deliberative forms of involvement, as emphasised in the responsible research and innovation movement, may also heighten impact by positioning citizens as active participants in the production of knowledge rather than passive consumers of it, allowing research to become more responsive and adaptive to grand challenges (e.g. European Commision 2013; Sauermann et al. 2020).

As mentioned above, however, assessing the societal impact of research and innovation is a tricky exercise marked by challenges that include causality, attribution, national borders, and time delays (Nightingale and Scott 2007; Bornmann 2013). The application of OIS practices may further exacerbate these challenges. For example, when reviewing research proposals in terms of societal impact, it is difficult to find reviewers with the capacity to evaluate at different stages and from different perspectives (Holbrook 2005). More generally, the (scientific) outputs of an expanded set of stakeholders can have a multitude of effects that can scarcely be captured by a single assessment mechanism (Molas-Gallart and Tang 2011).

3. Discussion and contributions

As the result of synthesising cross-boundary knowledge about open and collaborative practices in science, this article and the OIS Research Framework are poised to make at least three significant contributions. First, by taking an interdisciplinary, collaborative approach (see Appendix A for a detailed description), we bridge disciplinary differences in terms of underlying norms, theories, assumptions, methods, and languages. While open and collaborative practices are discussed in multiple scientific fields, an overall understanding of antecedents, contingencies, and consequences has been missing, in part due to these very real differences. Adding to the science of science literature (Brown, Deletic, and Wong 2015; Dasgupta and David 1994; Fortunato et al. 2018; Jones, Wuchty, and Uzzi 2008; Van Noorden 2015; Wuchty, Jones, and Uzzi 2007), we argue that a more complete understanding of the available knowledge is needed to manage processes of openness and collaboration in science. The co-creative approach we took to gathering and structuring this knowledge, which granted all participants equal decision rights, made it possible to aggregate knowledge of the scientific community about open and collaborative research practices, so as to avoid redundancies in future scientific efforts and to build a solid foundation for an ambitious research agenda. Our collaborative approach will hopefully inspire future interdisciplinary endeavours.

Second, this article and the framework it advances not only bridge disciplinary differences, but also highlight them in order to surface tensions and incongruities. For example, while economics might emphasise the role of incentives in shaping behaviour, sociology might focus on norms and institutional constraints. In doing so, each discipline relies on different assumptions about individual agency and social influence. Our framework poses questions about the conditions under which one or another perspective has more explanatory power, as well as how they could be aligned and integrated. Similar dynamics are at work with the methodological differences between disciplines, whose effects were observable when we considered the relative proportion and weight of descriptive studies, correlational quantitative work, field experiments, and other approaches in informing our framework. We argue that all of these methods have the potential to drive future research activities, perhaps especially through their integration. For example, heavily quantitative fields such as economics could benefit from richer qualitative understanding, while qualitative traditions could be enriched by the larger-scale insights and opportunities for causal identification that quantitative approaches can provide. Beyond disciplinary differences as such, involving natural scientists and other practitioners in the process of conceptualising the framework and writing this article also brought their unique experiential knowledge into discussions, even as they reported benefiting from the 'outsider' perspective of social scientists.

Third, by providing a comprehensive view of different aspects of OIS and structuring it in terms of practices, multi-level antecedents and boundary conditions, as well as outcomes and impacts, our framework suggests specific connections and interdependencies. For example, while some attention has been given to individual-level drivers of open and collaborative behaviours, these drivers need to be seen in the broader context of the organisation and even field level (e.g. Cohen, Sauermann, and Stephan 2020, which shows that motives for commercialisation and their impact differ systematically across fields). Future research should examine the interdependencies between different levels of analysis; while this approach will require resourcefulness in collecting data across levels, the pay-off will be an ability to offer richer analyses that do justice to the complexity of the science system. Research designs that cross levels of analysis in this way promise a deeper understanding of OIS and stand to have important implications for the spheres of practice and policy. The OIS Research Framework also points to potential tensions and conflicts that may arise in pursuit of purposefully opening the scientific research process. For example, greater openness with respect to research data and other outputs may undermine efforts at technology commercialisation, which typically requires appropriation. Likewise, when designing the implementation of certain practices, attention will need to be paid to the multiple functions that these practices might have and the potential existence of trade-offs between them (e.g. citizen science can result in both scientific and broader societal impacts). These essential tensions (Hackett 2005) and interdependencies are, in our view, at the heart of research on openness and collaboration in science.

Taking these points together, we want to conclude by outlining potentially fruitful avenues for future research that emphasises interrelations, contradictions, conflicts, and tensions, as well as the robust findings presented in the previous sections.

4. Future research on Open Innovation in Science (OIS)

Mapping the contemporary state of knowledge across the OIS research landscape inevitably leads to the identification of gaps that future research may seek to address in advancing our understanding of the antecedents, contingencies, and consequences of open and collaborative practices in science. In this section, we highlight research gaps that directly relate to and evolve out of the OIS Research Framework, structuring them in terms of 1) OIS practices, 2) antecedents and contingencies, and 3) outcomes and impacts.

Regarding OIS practices themselves, many of those involving both academic and non-academic stakeholders have been described above. However, these practices are each grounded in particular networks of stakeholders, institutional logics, and conventional domains of application. Drawing connections between them as instances of purposively managed knowledge flows across boundaries both challenges prior assumptions and carries new potential. Future research must therefore begin to uncover synergies and complementarities between these practices as they function within the scientific environment. For example, the use of crowdsourcing could take on a new civic aspect if used to identify new research problems in conjunction with the practice of priority setting for mission-driven research (for an early experiment in this, see Beck et al. 2020).

Given the long time horizon for many scientific projects, interaction with collaborators may require more intense and longer-term engagement compared, for example, to the usually shorter cycle of innovation processes. This emphasises the need to better understand the time scales and rhythms of interaction between stakeholders for different OIS practices (Delvenne and Macq 2019). Conflicting goals may also complicate potential synergies between different OIS practices and stakeholders, as firms require appropriation and patenting while scientists may prefer openness of data and results (Vedel and Irwin 2017). To this end, the development of a multi-dimensional measurement scale of OIS practices, which captures the intensity of effort when applying certain practices alone or in combination, may be beneficial. This would allow future studies to assess the benefits and costs of applying OIS practices in new contexts more holistically or applying multiple practices simultaneously.

Future research also needs to advance our understanding of the multi-level antecedents and contingencies of OIS practices that influence the occurrence and success of open and collaborative practices in science. At the individual level, as discussed above, capabilities such as creativity have been found to influence open and collaborative behaviour, but less is known about how to build such capabilities at an early career stage or even during childhood (e.g. as a form of individual-level absorptive capacity). Further micro-level research is still needed to develop a more complete understanding of capabilities, attitudes, values, characteristics, and motivations around different OIS practices, as well as the interplay of those elements with each other and with contextual factors. Micro-level antecedents and contingencies for the public to engage in science, in particular, need to be further investigated. For example, research shows that motivations for participating in a citizen science project include learning new things, concern for others, self-improvement, social motivation, and expected benefits for future careers (West and Pateman 2016; Tinati et al. 2017). However, these motivations can vary depending on the intensity and maturity of a citizen's involvement, in conjunction with other factors like professionalism (Füller et al. 2017). The complex relationships between motivation, willingness, and capabilities clearly have effects not only for citizen science, but for any OIS practice that relies on actors from outside of academia. This highlights the importance of understanding self-selection into these roles so as to ensure fit with evolving task requirements.

On an organisational level, future research should assess how organisational design factors such as structures, processes, norms, and ownership models can support or hinder acceptance and successful application of OIS practices. This might involve creating spaces and incentives within organisations that allow scientists to experiment with OIS practices while reducing associated monetary, time, and career-related costs. These experiments, crucially, may involve piloting novel organisational forms beyond the received structures of departments, research centres, and the like. Such institutional changes should be aligned with policy-level efforts to encourage, monitor, and manage open and collaborative research practices while mitigating emerging risks (e.g. openly sharing research data while ensuring participants' data protection rights). In addition, technological advancements require ongoing attention to identify the potential for new research technologies like artificial intelligence and their implementation for OIS practices. For example, as discussed above, pioneering advances can already be observed in the area of computational citizen science, as well as in the creation of hybrid Open Science processes combining experts, crowds, and AI (Kittur et al. 2019).

On a policy level, regulations and guidelines need to be developed and aligned with activities at other levels to sustainably govern OIS practices. These might include research funding schemes that require the application of OIS or the widespread adoption of intellectual property mechanisms such as Creative Commons licences. Evaluation of these measures also should not take place in isolation, but in the context of a policy mix promoting a range of approaches to research (Cocos and Lepori 2020).

In terms of OIS-related outcomes and impacts, advocates of OIS often assume that OIS practices will have uniformly beneficial effects in scientific, economic, social, and even ethical terms. However, a more critical evaluation of OIS practices has yet to be undertaken, both theoretically and empirically. The former approach might draw on an often overlooked tradition of critical innovation studies (Godin and Vinck 2017), as well as recent efforts to problematise or assess the limits of scientific openness (Hartley et al. 2018) and collaboration (Oliver, Kothari, and Mays 2019). The latter raises the question of how to measure the outcomes and impacts of OIS as currently conceptualised; for instance, what should serve as key performance indicators for its scientific and societal impacts or for value captured as a result of its application? The framework put forward in this article presents many touchpoints for future research to connect with the creative and often critical work on research metrics and indicators (e.g. de Rijcke et al. 2016). To this end, mid- and long-term consequences for applying OIS practices – both positive and negative – need to be tracked and elaborated further for individual scientists, research teams or groups, and research organisations. Finally, while OIS practices hold the potential to contribute to a more balanced distribution of capacities for engaging in collaborative knowledge production processes (e.g. reducing some of the structural disadvantages faced by the Global South), more research is needed to determine whether OIS can live up to this promise.

In summary, the synthesis of existing knowledge about open and collaborative practices in science from many disciplines, schools of thought, and methods marks out a large research field that demands attention to the cross-cutting interdependencies of the overarching constructs, as well as to specific practices, antecedents, boundary conditions, and consequences.

5. Conclusion

In this article, we propose the concept of Open Innovation in Science (OIS) as a unifying foundation for advancing our understanding of antecedents, contingencies, and consequences related to applying open and collaborative practices along the entire process of generating and disseminating new scientific insights and translating them into innovation. While we believe that synthesising insights from multiple disciplines about openness and collaboration is a valuable first step in designing and managing efficient and effective processes for producing and disseminating scientific knowledge today, much remains to be done. By mapping the existing literature and offering a clear conceptualisation of the OIS research field, we hope to stimulate fruitful discussions, debates, and scientific efforts to tackle the gaps we have identified. Unleashing the power of open and collaborative practices may allow us to produce more novel and impactful scientific knowledge for the world, to meet the challenges of our time and, in doing so, to better serve the purposes of science.

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Appendix A

The collaborative conceptualisation approach and reflections

We took a collaborative approach to the entire process of conceptualising the OIS Research Framework and writing this article (see Table A). In particular, instead of presenting collaborators with a fixed framework from the beginning, we chose to co-create the framework from scratch in a collaborative two-day workshop at the first Open Innovation in Science Conference in 2019.[4] During the co-creation process, we aimed to share decision rights equally among all participants, discussing the structure and elements of the scientific research process, topics to include, as well as the order, levels of analysis, and interdependencies. The role of the special issue guest editors[5] was to facilitate and structure the collaboration rather than to intervene and delineate the path ahead.

This process did not come without challenges. Synthesising the broad range of different arguments without compromising on the content required several additional steps that were not planned in the beginning, but were necessary to define a common ground reflecting all perspectives. Thus, instead of beginning with the text of the article itself, we asked the co-authors to first collect the literature for the different boxes and arrows of the OIS Research Framework in nine tables (resulting in more than 200 entries). In doing so, we were able to identify similarities and differences before initiating the writing process. This also helped to surface some enriching discussions as we structured an outline of the article. Another challenge was time management. We would advise those planning future collaborative endeavours to keep the schedule flexible while informing all collaborators about changes and realistic time horizons for each task. This is particularly true for the later stages (i.e. steps 16–19 in Table A), during which individual contributions needed to be collected and integrated.

Table A: Overview of the collaborative conceptualisation process.

Task	Step Description	Duration
Stage 1: Collaborative conceptualisation at the first OIS Research Conference in 2019		
Develop initial OIS Research Framework	1. Presentation of a simple process model defining OIS 2. Individual reflection on missing or misplaced elements in the initial model 3. Random assignment of participants into groups to refine initial model 4. Group presentations of modified frameworks 5. Joint discussion of the resulting modifications until preliminary consensus was reached 6. Appointment of main coordinator to organise and structure the collaborative process	2 days
Stage 2: Collaborative outlining and writing of the article		
Refine the OIS Research Framework	7. Organising team (OT) refines OIS Research Framework by considering all materials, notes, and discussions from the conference 8. Refined framework is shared online with collaborators, who are invited to discuss	1 week
Rework the OIS Research Framework	9. OT incorporates the comments on the framework and resolves disagreements among co-authors. Based on the comments, the next steps for the collaborative writing process are designed.	6 weeks

(*Continued*)

[4](see https://ois.lbg.ac.at/en/research/ois-conference-2019)

[5]This article is part of a special issue of Industry & Innovation entitled ‘Open Innovation in Science.’ The guest editors are Susanne Beck, Christoph Grimpe, Marion Poetz, and Henry Sauermann.

Table A: (Continued).

Task	Step Description	Duration
Develop structure of main body	10. Collaborators gather the relevant literature streams in a shared document structured around the boxes and connecting arrows of the OIS Research Framework.	4 weeks
Edit storyline of main body	11. Based on co-authors' contributions, the OT pre-structures the article's subsections. This step aims to avoid redundancies in the text later.	5 weeks
Write introduction and main body	12. Co-authors write the introduction and main body of the article by developing main arguments in the form of bullet points, synthesising the previously collected insights from the literature (see step 10).	4 weeks
Edit main body I	13. OT edits the bullet points into text, thereby aligning content, language, writing styles, formats, etc. of the main body. 14. OT coordinates loops with co-authors to resolve disagreements.	5 weeks
Revise and continue to edit main body	15. All co-authors are invited to revise the main body, resolve individual and group disagreements, and finalise open tasks.	4 weeks
Edit main body II	16. OT synthesises, streamlines, and complements content to meet the journal's page limit. Particular attention was paid to preserving the arguments made by all co-authors and to shortening the text solely by synthesising and restructuring the content. This iterative process was realised in collaboration with co-authors.	12 weeks
Write and edit the discussion and future research sections	17. All co-authors are invited to collect future research opportunities and research gaps resulting from the existing state of OIS research. 18. OT synthesises input into a first draft of the discussion.	12 weeks (in parallel to step 16)
Final editing	19. OT reviews and edits the entire document and prepares it for final proofs.	15 weeks
Professional language editing	20. Article undergoes professional editing to align formulations and writing styles.	3 weeks
Final proofs	21. All co-authors are invited to review the manuscript.	1 week
Finish article	22. Article undergoes professional language check. OT enters final changes and finalises and submits the manuscript.	1 week

Note: OT = Organising Team.

Despite these challenges, we consider our collaborative approach to be well-suited to this undertaking for three reasons. First, scholars participating in this project have unique approaches towards and experiences with openness and collaboration in science, which allowed us to avoid overstating generalisability or misaligning potentially incompatible concepts. Given our diversity, we sought to align and balance the different literature streams rather than imposing one dominant logic. Second, different scientific fields across the humanities, social sciences, and natural sciences have different norms regarding the intensity and scope of different types of open and collaborative practices. These divergences informed the entire process, from conceptualising the framework to identifying the literature informing the antecedents, contingencies, outcomes, and impacts of OIS practices, to writing this article. The open and constructive attitude of the co-authors made it possible to identify and resolve conflicting (often tacit) assumptions. Third, we consider this unifying framework as a starting point for future joint research endeavours. Thus, we are relying on a strong network of scholars to apply, nurture, and further develop the OIS Research Framework. We hope that this article provokes rich discussions on open and collaborative practices in science and attracts new members of an emerging scientific community. Anyone interested in applying such an approach or learning more about it is welcome to contact the corresponding author for more information.