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Open Science in the digital era

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Abstract

Forefront technological breakthroughs empowered by big data, artificial intelligence, 3D printing, blockchain, and quantum computing have disrupted the established openness of the institution of open science in the digital era. They have introduced unprecedented possibilities and challenges to instantly, interactively, collaboratively, and responsibly perform science around the world in the digital era. This doctoral dissertation is aimed at a philosophical, sociological, and economic conceptualization of the normative structure of open science in the digital era, as well as revealing its impact on the established governance of research and innovation at universities. I present a systematic literature review and two empirical studies on how new digital technologies and tools, together with new open physical and digital infrastructures, have disrupted the openness of the institution of open science in the digital era in universities and are remodelling their science and innovation practices, cognitive norms, and processes and challenging their existing cultures, missions, and policies. With these three articles, I analyse the foundations of the institution of open science, the evolution of its openness, and the transformation of the institution in the digital era. I investigate the definition, practices, norms, and goal of open science and the role of scientists in the digital era within the context of its main public infrastructure: universities. With Article 1, we develop a rigorous, integrated, and up-to-date definition of open science through a systematic literature review. With Article 2, based on a qualitative empirical research study taking a grounded theory methodological approach, we identify emergent principles, practices, and underlying mechanisms of open science and innovation developed and encountered by research teams at universities. With Article 3, through a qualitative empirical research study using a thematic coding and analysis, we understand how existing and recently adopted open science practices and underlying principles and attitudes of research teams support the advancement of knowledge and the development of actions, solutions, and technologies for sustainable development. This doctoral dissertation lays the philosophical, sociological, and economic foundations of an expansive institution of open science in the digital era. The definition provides a comprehensive view of the streams of knowledge on the institution. The expansive normative structure of open science – its goal, norms, and practices – articulates the institution and provides a robust framework for its theoretical analysis in the digital era. This doctoral dissertation also identifies a new academic entrepreneurial ethos that advances the role of researchers at universities. Additionally, this doctoral dissertation provides the grounds for understanding how the institution of open science is shaping open innovation at universities in the digital era. Open science is expanding and laying the foundations of open exploration, an expansive model of university research and innovation in the digital era. Finally, this doctoral dissertation provides novel insights into and important suggestions regarding the advancement of open science, innovation policies and governance reforms at universities for enhancing a sustainable world.

Keywords open science; public science policy; university governance; open innovation; science and innovation policy; open exploration; sustainability

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Contents

List of Abbreviations and Symbols

CUDOS	Communalism, Universalism, Disinterestedness, and Organised Scepticism
DG	Directorate General
EC	European Commission
EU	European Union
JUFO	Finnish journal ranking system
GDPR	General Data Protection Regulation
IT	Information Technology
MOOC	Massive Online Open Course
NGO	Non-Governmental Organization
OECD	Organisation for Economic Cooperation and Development
UN	United Nations

List of Publications

This doctoral dissertation consists of a summary and of the following publications which are referred to in the text by their numerals

1. Vicente-Saez, R., Martinez-Fuentes, C., 2018. Open Science now: A systematic literature review for an integrated definition. Journal of Business Research 88, 428–436. doi: 10.1016/j.jbusres.2017.12.043

2. Vicente-Saez, R., Gustafsson, R., Van den Brande, L., 2020. The dawn of an open exploration era: Emergent principles and practices of open science and innovation of university research teams in a digital world. Technological Forecasting and Social Change 156. doi: 10.1016/j.techfore.2020.120037

3. Vicente-Saez, R., Gustafsson, R., Martinez-Fuentes, C. Opening up science for a sustainable world: An expansive normative structure of open science in the digital era. Submitted to the journal Science and Public Policy in September 2020. First revision requested submitted in March 2021. Second revision requested submitted in May 2021.

Author's Contribution

Article 1: Open Science now: A systematic literature review for an integrated definition

Leading author and project lead. Development of the research idea and main responsibility in all aspects of the study. Clara Martínez-Fuentes supported the development of the research idea, participated in the design of the systematic literate review and the data analysis, and provided comments and suggestions for the writing of the article.

Article 2: The dawn of an open exploration era: Emergent principles and practices of open science and innovation of university research teams in a digital world

Leading author and project lead. Development of the research idea and main responsibility in all aspects of the study. Robin Gustafsson supported the development of the research idea, participated in the design of the empirical study and the data analysis and contributed significantly to the writing of the article. Lieve van den Brande provided comments and suggestions for the writing of the article.

Article 3: Opening up science for a sustainable world: An expansive normative structure of open science and innovation in the digital era

Leading author and project lead. Development of the research idea and main responsibility in all aspects of the study. Robin Gustafsson supported the development of the research idea, participated in the design of the empirical study and the data analysis, and contributed significantly to the writing of the article. Clara Martínez-Fuentes provided comments and suggestions for the writing of the article.

1. Introduction

In the new century, there are no barriers, distances do not exist, and the Net is universal.
In the new era, communication is instantaneous, and your dreams come true.
Introduction of the radio programme *Journey to the Polar Dreams* (1998)

Uudella vuosisadalla ei ole esteitä, etäisyyksiä ei ole, Verkko on universaali.
Uudella aikakaudella viestintä on välitöntä, ja unelmasi toteutuvat.
Radio-ohjelman esittely: *Matka napaunelmiin* (1998)

En el nuevo siglo no hay barreras, las distancias no existen, la Red es universal.
En la nueva era, la comunicación es instantánea, y tus sueños se cumplen.
Intro del programa de radio: *Viaje a los sueños polares* (1998)

Openness is a philosophical principle that has guided societies' progress across eras. Science, from the Latin word *scientia*, means knowledge. Openness in science has centred on the aspiration of achieving human progress through reason and scientific knowledge since its emergence. From the Age of Enlightenment to today (what I refer to as the technological age of the digital era), the openness of the institution of modern or open science – that is, openness in science practices, norms, and goal (Merton, 1973) – has expanded. The openness of the institution has evolved in accordance with each period's technological, socio-cultural, economic, and political constructs (David, 2004a). Current technological breakthroughs empowered by big data, artificial intelligence, the Internet of Things, machine learning, synthetic biology, 3D printing, blockchain, and quantum computing have disrupted the established openness of the institution in the digital era. They have introduced unprecedented possibilities and challenges to instantly, interactively, collaboratively, and responsibly perform science around the world in the digital era (Owen et al., 2012; Bogers et al., 2018). However, these digital technologies have introduced more than a technology-driven change in scientific knowledge-making (Burgelman et al., 2019). These technologies are reconfiguring the philosophical, sociological, and economic structure of the institution of open science. Advances in not only the use of these new digital technologies and tools, but also of new open physical and digital infrastructures for science inquiry, are facilitating the rise of a second open scientific paradigm for further exploration in the digital era (Nielsen, 2011; Bartling and Friesike, 2014). New opportunities for expanding openness are transforming the institution of open science in the digital era. Distinctive schools of thought involving scientists, policymakers, and citizens have explored the democratic, pragmatic, infrastructural, public,

and metrical foundations of this emerging scientific movement (Fecher and Friesike, 2014). However, how this second open scientific paradigm is articulated by researchers within the institution of open science and implemented in its main public infrastructure in the digital era remains to be discovered.

This doctoral dissertation is aimed at a philosophical, sociological, and economic conceptualization of the normative structure of open science in the digital era, as well as revealing its impact on the established governance of research and innovation at universities. I present a systematic literature review and two empirical studies on how new digital technologies and tools, together with new open physical and digital infrastructures, have disrupted the openness of the institution of open science in the digital era in universities and are remodelling their science and innovation practices, cognitive norms, and processes and challenging their existing cultures, missions, and policies. With these three articles, I analyse the foundations of the institution of open science, the evolution of its openness, and the transformation of the institution in the digital era. I investigate the definition, practices, norms, and goal of open science and the role of researchers in the digital era within the context of its main public infrastructure: universities.

Article 1 comprehensively explores the second open scientific paradigm's distinctive philosophical foundations and schools of thought. The purpose of this article is to develop a rigorous, integrated, and up-to-date definition of the open science phenomenon in the digital era. First, based on a systematic literature review conducted with an interdisciplinary research approach, the article defines open science in the digital era as "transparent and accessible knowledge that is shared and developed through collaborative networks" (Vicente-Saez and Martinez-Fuentes, 2018, pg. 434). Second, the article specifies that the openness of the institution of open science in the digital era follows two dynamics: openness in the sharing of knowledge and openness in the production of knowledge. Finally, the article reveals that openness in science is anterior to openness in innovation and is inspired by the Mertonian norms of communalism, universalism, disinterestedness, originality, and scepticism (CUDOS norms) (Merton, 1942, in Merton, 1973).

Article 2 analyses the evolution and impact of this second open scientific paradigm in universities, which constitute the main public infrastructure for open science. The purpose of this article is to identify the emergent principles, practices, and underlying mechanisms of open science and innovation developed and encountered by research teams at universities. First, through qualitative empirical research using a grounded theory methodological approach, the article identifies four key principles of open science in the digital era: transparency and accessibility of science outputs and authorization and participation in science production. Second, it identifies two types of open science practices adopted by research teams: open sharing practices and open inviting practices. Third, it reveals the factors that promote and prevent the development of open science practices in university research teams. Finally, it shows how the adoption of new open science practices and principles by pioneering research teams is triggering novel open innovation practices in universities, such as inbound and outbound product and service innovations. All key findings are synthesized into a conceptual model for the governance of open science and innovation at universities in the digital era.

Article 3 explores the transformation of the institution of open science in the digital era. The purpose of this article is to understand how existing and recently adopted open science practices and the underlying principles and attitudes of research teams support the

advancement of knowledge and the development of actions, solutions, and technologies for sustainable development. It is also aimed at understanding the challenges research teams face when adopting novel open science and innovation practices. Through qualitative empirical research using thematic coding and analysis, this article reveals the expansive norms and institutional goal of open science in the digital era. Based on this analysis, it infers an expansive normative structure of open science among researchers working on sustainability, including institutional goal, norms, and practices, enabled by the active use of digital technologies and tools and open physical and digital infrastructures by research teams. The goal of open science in the digital era has evolved to encompass the expansion of informed and extended knowledge co-creation. Next, it reveals a major development in open science practices that has occurred in sustainability research among pioneering research teams. When combating climate change and its impacts, research teams' major open sharing practice is open data, and transdisciplinary research is their major open inviting practice. Finally, it shows how researchers are becoming increasingly entrepreneurial in their work and discusses how they have gone beyond existing research methods by being innovative and entrepreneurial in establishing knowledge co-creation activities and being explorative in knowledge value creation, circulation, and recombination work. The study also identifies a new academic entrepreneurial ethos based on the adoption of the expansive norms of open science; a mindset focused on radical creativity, initiative, and passion for exploring new innovative solutions; and the promotion of responsibility and inclusiveness as key values. This new academic entrepreneurial ethos can be considered itself an institutional model for universities working on sustainability in the digital era.

This doctoral dissertation lays the philosophical, sociological, and economic foundations of an expansive institution of open science in the digital era. The definition provides a comprehensive view of the streams of knowledge on the institution. The expansive normative structure of open science – its goal, norms, and practices – articulates the institution and provides a robust framework for its theoretical analysis in the digital era. This doctoral dissertation also identifies a new academic entrepreneurial ethos that advances the role of researchers at universities. Additionally, this doctoral dissertation provides the grounds for understanding how the institution of open science is shaping open innovation at universities in the digital era. Open science is expanding and laying the foundations of open exploration, an expansive model of university research and innovation in the digital era. In addition, this doctoral dissertation provides novel insights into and important suggestions regarding the advancement of open science, innovation policies, and governance reforms at universities, as well as open science recommendations, policies, programmes, and actions for enhancing a sustainable economy, society, and environment in the digital era. Finally, this doctoral dissertation presents three possible building blocks for advancing the opening of science for enhancing a sustainable world.

This doctoral dissertation is organized as follows. In Section 2, I present the theoretical framework for the evolution of open science and the university. Next, in Section 3, I present the three articles' purpose, methods, and key findings. In Section 4, I present a discussion of the findings and their theoretical and practical implications for the present and future of the open science in the digital era. Finally, in Section 5, three possible building blocks to move from the technological age of the digital era towards one focused on human progress: the humanist age of the digital era.

2. The evolution of openness and the university

In this section, I synthesize the philosophical, historical, sociological, and economic streams of knowledge on the institution of open science to build a comprehensive theoretical framework for the rationales and dynamics of the institution in the digital era.

2.1 The openness of the institution of open science across the eras

The foundations of the modern or open science institution emerged with the ideals of the scientific revolutions of the late 16th and 17th centuries in Western Europe (Merton, 1938, in Merton, 1973; David, 1998). However, openness predates the institution of open science. Openness has been embedded in our civilizations since the emergence of philosophy in Greece. Natural philosophers, or pre-Socratics, explained the processes of nature by moving from myth-based reasoning towards one based on experience and reason (Curd, 2020). Socrates, with his ideas and method, encouraged others to explore their own knowledge (Nails, 2020). Plato, with his theory of ideas illustrated in the Allegory of the Cave in *The Republic*, launched a dialogue in society about the importance of exploring the borders of conventions through knowledge (Kraut, 2017; Partenie, 2018). Aristotle, a natural philosopher and biologist, shaped and opened to society over centuries the frontiers of learning through his systematic organization of the sciences as theoretical, practical, and productive (Shields, 2020). The achievements of ancient classical civilization in philosophy (standards of reasoning) and the development of teaching and research bodies (standards for the advancement of knowledge), such as the Lyceum (school, library, and laboratory of philosophy) and the Museum (first state-funded research and teaching institute operating in all the then-known areas of knowledge), established the grounds for the later institutionalization of modern or open science (Redner, 1987). Greek philosophers opened up reasoning and knowledge to their society as an underlying evolutionary mechanism for achieving progress. Philosophers developed the rationale of openness, and with it, they challenged and advanced the established socio-cultural, economic, and political systems of their eras. Openness, then, is a philosophical principle that has guided and supported the progress of our societies through reason and knowledge across the eras.

Openness enabled evolution across the eras, from the medieval to the early modern, and from the early modern to the late modern. However, especially far-reaching evolution occurred during the Age of Enlightenment, when philosophers (proponents of openness) and scientists (proponents of science) joined forces. Openness founded on reason and the sharing of scientific knowledge led to the first open scientific paradigm. Philosophers and scientists shared openly

and promoted new ideals and ideas for human progress together. In other words, they inspired each other to achieve progress. Openness was key to improving scientific inquiry through new practices – enabled by the prior development of printing technology – for the disclosure and dissemination of new discoveries. Openness was fundamental for establishing a new set of social cognitive norms and incentives among scientists, as well as achieving independent and reliable scientific bodies that pursued public knowledge for progress (David, 2014). Openness inspired the foundations (*definition*) of open science in the late 16th and 17th centuries and articulated the institution (*practices, norms, goal*) in the scientific bodies (*infrastructure*) during the Enlightenment.

From the Age of Enlightenment until today (what I refer to as the technological age of the digital era), the openness of the institution of open science – that is, *openness in science* – has evolved in accordance with the technological, socio-cultural, economic, and political constructs of each period (David, 2004a). Advances in the openness of the institution have brought about different historical systems of scientific organization (Mirowski, 2018). Current technological breakthroughs empowered by big data, artificial intelligence, the Internet of Things, machine learning, synthetic biology, 3D printing, blockchain, and quantum computing have disrupted the established openness of the institution. These have introduced unprecedented possibilities and challenges to instantly, interactively, collaboratively, and responsibly perform science around the world in the digital era (Owen et al., 2012; Bogers et al., 2018). However, these digital technologies have introduced "more than a technology-driven change" in scientific knowledge-making (Burgelman et al., 2019). These technologies are reconfiguring the philosophical, sociological, and economic structure of the institution of open science. Advances in not only the use of these new digital technologies and tools, but also of new open physical and digital infrastructures for science inquiry, are facilitating the rise of a second open scientific paradigm for further exploration in the digital era (Nielsen, 2011; Bartling and Friesike, 2014). New opportunities for expanding openness are transforming the institution of open science in the digital era. Distinctive schools of thought involving scientists, policymakers, and citizens have explored the democratic ("knowledge freely available for everyone"), pragmatic ("knowledge creation that is more efficient and goal oriented"), infrastructural ("open platforms, tools, and services for scientists"), public ("science accessible for citizens"), and metrical ("alternative metric system for science impact") foundations of this emerging scientific movement (Fecher and Friesike, 2014). However, how this second open scientific paradigm is articulated by researchers within the institution of open science and implemented in its main public infrastructure – universities – in the digital era remains to be discovered.

The openness of the institution of open science in the digital era follows two dynamics. First, there is openness in the sharing of knowledge, as evidenced by Bisol et al. (2014), David (1998), the European Commission (2016), Grand et al. (2016), and Labastida (2015). Second, there is openness in the production of knowledge, as illustrated by the European Commission (2015, 2016), Grand et al. (2016), Friesike et al. (2015), Fry et al. (2009), and Hormia-Poutanen and Forsström (2016). Indeed, openness in science in the digital era goes beyond open access practices and policies. Examples of more recent open science practices adopted by research teams include open data, open labs, crowdsourcing practices (Fecher and Friesike, 2014), and transdisciplinary research practices (OECD, 2020) aimed at sharing and developing scientific knowledge among researchers, universities, citizens, research institutes, companies, NGOs, municipalities, states, and international organizations. These new open science practices

contribute to the evolution of the traditional knowledge creation process: the research process (Mukherjee and Stern, 2009; Lang et al., 2012; Mauser et al., 2013). The research conducted during the past five years, summarized in this doctoral dissertation, contributes to the advancement of the emerging stream of knowledge in open science research by laying the foundations for the theoretical analysis of this institution in the digital era.

2.2 Open science public infrastructure in the digital era

Openness founded on reason and the sharing of scientific knowledge led to the first open scientific paradigm. The adherence of scientists to new cognitive norms and new practices for the disclosure and dissemination of new discoveries challenged the organizational structures for performing science in that era (David, 2014). During the Enlightenment, universities, medieval organizations for the professional practice and learning of knowledge, promoted reactionary academicism, which prevented the adoption of modern or open science (Redner, 1987). The openness of the first open scientific paradigm challenged universities' governance models, that is, their authority structure. As result of this paradigm, the university moved from being a "church-controlled clerical institution" towards a "state-controlled scientific institution" (Redner, 1987; pg. 37).

Novel open science practices (Burgelman et al., 2019; Friesike et al., 2015; Mukherjee and Stern, 2009) of the second open scientific paradigm, adopted by researchers, are impacting universities' research agendas, science reward systems, talent management systems, and public engagement instruments and mechanisms. These novel practices are impacting the governance model of universities, the main public infrastructure for implementing the institution of open science in the digital era, and, with it, the efficiency of the research system.

In this context, based on lessons learned from historical studies (Redner 1987; Daston, 2006) on the circumstances in which open science's public infrastructures emerged, and with the aim to achieve neutral, independent, reliable, and robust infrastructures in the future (David, 1998; 2004 a, b; 2014), I open a discussion on further analysis in the field of open science research. Specifically, what public infrastructure – university – typology does our society need in the digital era to articulate the institution of open science for human progress? What profound governance changes must be undertaken for its efficient deployment? The answers to these questions are central to designing and fostering efficient public science policies, redesigning efficient research systems, and increasing human progress for all in the digital era. Open science is a driver for social and economic growth (David, 1998), and in the digital era, open science is also a driver for enhancing sustainability.

2.3 Expansive open science in the digital era

Science has always challenged other social institutions (Merton, 1938, in Merton, 1973), such as educational systems, economic systems, innovation systems, employment and labour mobility, competition and trade rules, and research systems. In the digital era, advances in the use of digital technologies and tools, as well as open digital and physical infrastructures, are not only transforming the institution of open science, but also impacting universities' ingrained

science and innovation mindsets, norms, practices, structures, and policies to engage in solving grand societal challenges, such as sustainability and climate change.

Novel open science practices adopted by researchers during the last 15 years, such as open data (Murray-Rust, 2008), open access publishing (Cribb and Sari, 2010), open protocols, open physical labs, crowdsourcing practices, and transdisciplinary research platforms, are challenging universities' second and third missions: research and the transfer of knowledge and technology. These challenges arise, for instance, in relation to reliable data sharing, quality control and reproducibility of research methods and results, and the management of joint research platforms, university-industry relations, strategic alliances, spin-offs, start-ups, and consortia.

Novel open science practices go beyond Merton's conventions and visions for science. These practices are currently expanding the institutional imperatives of communalism, universalism, disinterestedness, and organized scepticism (CUDOS norms) (Merton, 1942, in Merton, 1973) that synthesize the ethos of science to wider audiences and participants in science sharing and making. New open science practices and novel ways of organizing science work for researchers are making science increasingly accessible to citizens, knowledge freely available for everyone, scientific outputs more available, and the process of knowledge creation more collaborative, efficient, and goal oriented (Tacke, 2010). These open science policies and practices are also disrupting universities' established open innovation principles, practices, goals, and governance structures. Universities are encouraged to deconstruct their foundations (Perkmann, 2013; Smart et al., 2019) and re-examine their governance models to harness the potential of the institution of open science in the digital era.

In the digital era, universities are the natural institutional demarcations, that is, the main public infrastructure for open science (David, 2004a) and for open innovation (Perkmann and West, 2014). Indeed, universities are active players in open science and innovation practices (Bedford et al., 2018; Ayris et al., 2018) that foster research and innovation processes at the global, regional, national, and local levels. Openness in science and openness in innovation are not separate concepts (McMillan et al., 2014). Open science and innovation practices at universities constantly fuel each other. The institution of open science in the digital era is shaping open innovation (Dahlander and Gann, 2010). Indeed, the institution of open science is expanding. Open science and innovation practices constitute an emerging research field, and multiple levels of analysis are necessary to further develop them in various scholarly communities (Vicente-Saez et al., 2020).

3. Articles

In this section, I synthetize the articles' purpose, methods, data, and key findings. With these three articles, I analyse the foundations of the institution of open science, the evolution of its openness, and the transformation of the institution in the digital era, within the context of its main public infrastructure: universities. Article 1 comprehensively explores the second open scientific paradigm's distinctive philosophical foundations and schools of thought. Article 2 analyses the evolution and impact of this second open scientific paradigm in universities. Article 3 explores the transformation of the institution of open science in the digital era. Finally, I present a summary of the key findings of three articles and illustrate how these articulate the second open scientific paradigm within the institution of open science.

3.1 Article 1. Open science now: A systematic literature review for an integrated definition

Vicente-Saez, R., Martinez-Fuentes, C., 2018. Open Science now: A systematic literature review for an integrated definition. Journal of Business Research 88, 428–436. doi:10.1016/j.jbusres.2017.12.043

The purpose of this article was to develop a rigorous, integrated, and up-to-date definition of the open science phenomenon in the digital era through a systematic literature review.

We conducted a study based on an interdisciplinary approach (Booth et al., 2012). We combined a review protocol based on the Cochrane Collaboration approach (Higgins and Green, 2011); the four sequential steps of the Search, Appraisal, Synthesis and Analysis (SALSA) framework (Grant and Booth, 2009); and the Aristotelian method (Aristotle's Logic - Stanford Encyclopedia of Philosophy, 2015) to develop a definition based on the analysis of a final database of 75 studies (67 articles from reference journals and 8 focused reports from intergovernmental institutions).

Based on our systematic literature review, we reveal that open science in the digital era is "transparent and accessible knowledge that is shared and developed through collaborative networks". This definition is rigorous because it was built on reliable sources, including the IsI Web of Science Core Collection, Scopus, and international databases from intergovernmental organizations worldwide. It is integrated because it encompasses the emerging trends and practices of open science, such as open data, open access, science blogs, collaborative bibliographies, and citizen science. This definition is up to date inasmuch as it collects all evidence from the start of the open science phenomenon, from definitions or approximations based on the principles and values of Merton (1942, in Merton 1973), Chubin (1985), Dasgupta

and David (1994), David (1998, 2004a, 2004b), and Nelson (2003) to the definitions of Nielsen (2009), Friesike et al. (2015), the OECD (2014, 2015), Szkuta and Osimo (2016), Grand et al. (2016), Cottey (2016), and the European Commission (2015, 2016), among others.

Finally, our study also reveals two key findings affecting the conceptualization of openness in science in the digital era. First, we found that the openness of the institution of open science is embedded in knowledge production and sharing. This new openness in science goes beyond the disclosure and dissemination of knowledge among scientists. It also includes collaborative networks of participants in research (scientific, professional, and amateur users of scientific knowledge) in the pursuit of both sharing and producing knowledge. Second, we found that openness in science is inspired by the Mertonian CUDOS norms (Merton, 1942, in Merton, 1973), and not the values of openness in innovation. When designing the systematic literature review, we chose 2006 as a starting point for data collection because, from this year on, open innovation began to gain force and spur open and cooperative ideas in other fields, such as education and science. However, during our full-text sift data analysis, we found that some authors cited and used open science definitions or approximations (David, 1998, 2004a, 2004b; Dasgupta and David, 1994) based on principles and values from before 2006 when referring to the new openness in science. Openness in science therefore predates and encouraged openness in innovation. Open innovation was articulated in the same public infrastructure as open science: universities.

3.2 Article 2. The dawn of an open exploration era: Emergent principles and practices of open science and innovation of university research teams in a digital world

Vicente-Saez, R., Gustafsson, R., Van den Brande, L., 2020. The dawn of an open exploration era: Emergent principles and practices of open science and innovation of university research teams in a digital world. Technological Forecasting and Social Change 156. doi:10.1016/j.techfore.2020.120037

The purpose of this study was to identify emergent principles, practices, and underlying mechanisms of open science and innovation developed and encountered by research teams at universities.

We conducted a qualitative empirical research study (Gephart, 2004) using a grounded theory methodological approach (Glaser and Strauss, 1967; Corbin and Strauss, 1990; Corbin and Strauss, 2008). We studied novel open science and innovation practices at Aalto University in Finland. Aalto University was established in 2010 as a merger between three universities in the capital region: a technical university, a business school, and an art and design university. One of the key rationales behind the merger was the promotion of new multidisciplinary research and innovation practices between science, business, and industrial design researchers and practices that embrace openness in science and innovation. We studied 15 research teams to understand what principles and practices they use to engage in open science, what factors promote and prevent the adoption of open science practices, and what practices the teams use to transform open science outcomes into open innovation outcomes. Our selection criteria included research groups from the disciplines of science, business, and art and design; groups that had engaged in multidisciplinary research; and groups that had to some degree been forerunners or active in either open science or open innovation activities (or

both). We conducted semistructured interviews with research team leaders. We also made observations of the research teams' physical and digital workspaces, labs, and tools.

Based on our empirical research study, we first distinguished four key principles of open science in the digital era that direct the work of research teams at universities: transparency and accessibility of science outputs and authorization and participation in science production. Each principle of openness in science responds to a distinct question related to open science. These principles indicate which aspects of open science are, in fact, open in the digital era.

Second, through our study, we identified two types of open science practices that have been adopted by research teams: open sharing practices and open inviting practices. In all of the open sharing practices we identified – open data sharing, open access publishing, open protocols, open repositories, and open prototypes – the research teams were engaged in and oriented towards spreading novel scientific knowledge in society. All of the open inviting practices we identified – open collaborative tools, open physical labs, crowdsourcing practices, co-creation platforms, participatory design, and transdisciplinary research platforms – were, in contrast to the open sharing practices, oriented towards attracting individuals, other researchers, and groups and members of society to participate widely in research and create new scientific knowledge.

Third, our study revealed factors that promote and prevent the adoption of open science practices in university research teams. Open science policies, open science research field traditions, the open learning culture of the research team, and research team leaders' ideologies promoted the adoption of open science practices. Furthermore, intellectual property laws governing research teams (university regulation and/or national or EU laws); lack of incentives for research career development; lack of standards regarding data governance, infrastructure, practices, publishing protocols, skills, and technical support; misconceptions of what open science entails; and confusing publishing practices prevented the adoption of open science practices.

Finally, we revealed how the adoption of new open science practices and principles by pioneering research teams has inspired two novel open innovation practices in universities: inbound and outbound product and service innovations. We identified a novel type of inbound open innovation practice founded on the use of open science outputs to create product or service innovations in research teams at universities. This practice refers to the use of open science outputs to build and develop new applications and innovations that solve societal, economic, and cultural challenges. The other novel open innovation type, outbound open innovation practice, is founded on the use of open science outputs to promote the creation of product and service innovations by anyone. This practice refers to the refinement and sharing of open science outputs with foci of enabling societal, economic, and cultural value. We synthesize our key findings into a conceptual model for the governance of open science and innovation at universities in the digital era (Figure 1).

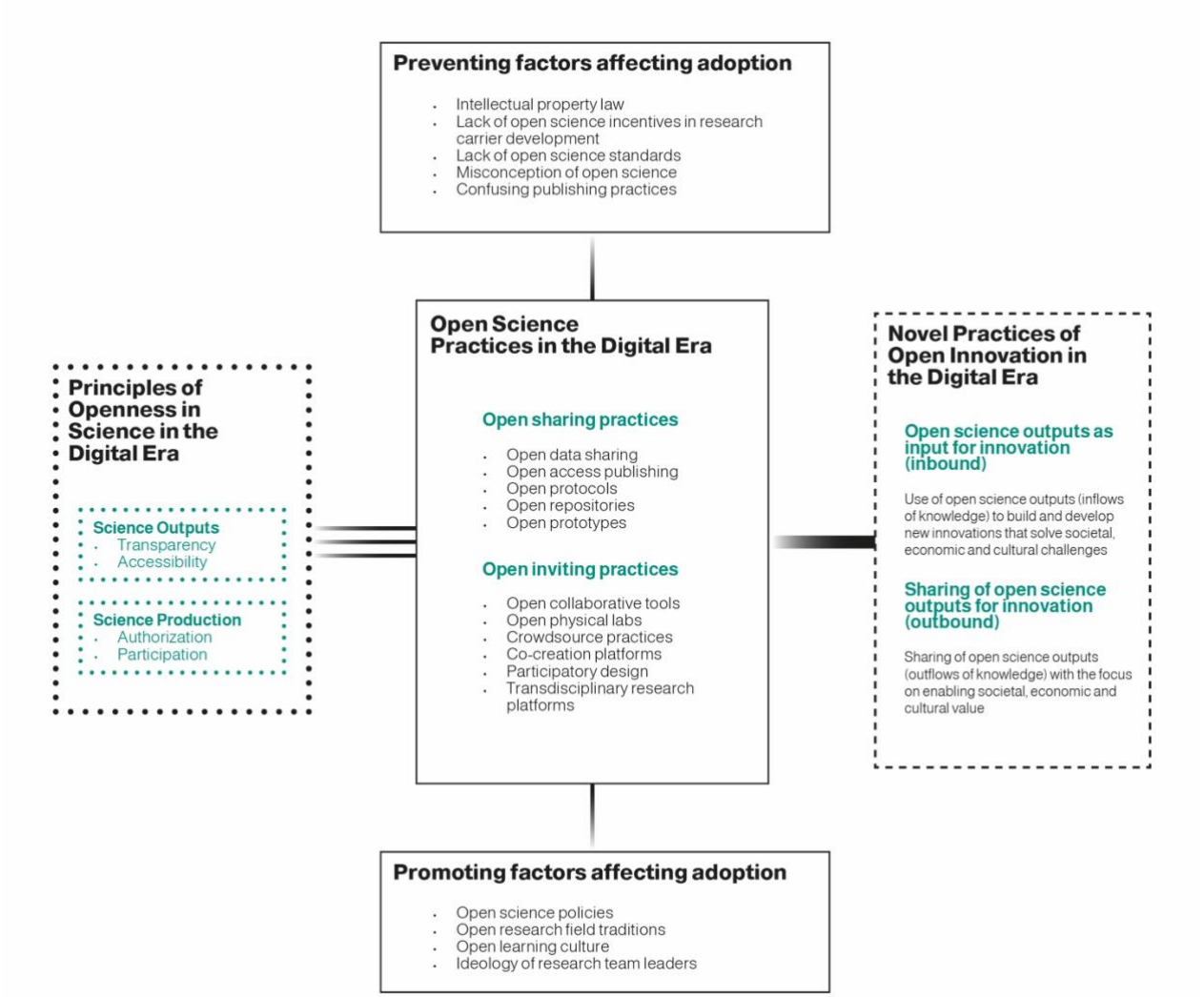

Figure 1. A conceptual model for the governance of open science and innovation at universities in the digital era.

3.3 Article 3. Opening up science for a sustainable world: An expansive normative structure of open science in the digital era

Vicente-Saez, R., Gustafsson, R., Martinez-Fuentes, C. Opening up science for a sustainable world: An expansive normative structure of open science in the digital era. Submitted to the journal Science and Public Policy in September 2020. First revision requested submitted in March 2021. Second revision requested submitted in May 2021.

The purpose of this empirical study was to understand how existing and recently adopted open science practices and the underlying principles and attitudes of research teams support the advancement of knowledge and the development of actions, solutions, and technologies for sustainable development. We also wanted to understand the challenges research teams have encountered when adopting novel open science and innovation practices. The specific objectives of our study were to first expose how the four principles of openness in science – transparency, accessibility, authorization, and participation (Vicente-Saez, Gustafsson, and Van den Brande, 2020) – have been present in research teams working on sustainability, specifically in the area of climate change. Second, we aimed to identify commonalities as well

as distinctive features in open science practices adopted by research teams working on climate change issues. Third, we analysed both the efficiencies gained and the key challenges prevalent in opening up science encountered by research teams. Finally, we aimed to identify the impact of open science practices on the role of researchers and their teams when researching and developing actions, solutions, and technologies for sustainable development.

We conducted a qualitative empirical research study (Gephart, 2004; Edmondson & McManus, 2007; Bansal et al., 2018) using thematic coding and analysis (Fereday and Muir-Cochrane, 2006; King and Brooks, 2018a) with a hybrid process of inductive and deductive analysis to analytically explore and capture the richest features of the data. We studied the practices of 23 research teams at Aalto University in Finland during 2019 from the disciplines of science, engineering, art, design, architecture, electrical engineering, and chemical engineering. Finland is an excellent location to study the open science practices of research teams working on topics related to developing solutions for a sustainable future. Finland has been a forerunner in the EU in promoting open science and innovation and has recently been proactive in opening up public data and creating open research infrastructures. Finland is committed to promoting openness as a fundamental value and to integrating open science practices into researchers' everyday work, as stated in the Finnish Declaration of Open Science and Research 2020-2025 (Federation of Finnish Learned Societies, 2020). Finland has a strong reputation as a country spearheading sustainable development (Kepa, 2017). Fully in line with Europe's vision and consistent with EU policies, Finland is playing an active role in implementing the 2030 UN Agenda for Sustainable Development at the national level and internationally. All the teams we studied perform fundamental and applied research and innovation work that addresses the grand challenge of combating climate change and its impacts – the UN's Sustainable Development Goal 13. Our sample is a solid, descriptive, and scalable representation of the Finnish and EU context for the accomplishment of the 2030 UN SDGs Agenda. These research teams are neutral representatives of their area and small-medium groups of early career and consolidated researchers. They are supported by university, national, and international funds. The research teams are all internationally active in conducting research, contributing to and using research, and defining problems and solutions with collaborative networks when working on topics related to combating climate change and its impacts. We conducted semistructured interviews with research team leaders. We also made observations of the research teams' physical and digital workspaces, labs, and tools. We built on the recent open science practice typology developed by Vicente-Saez, Gustafsson, and Van den Brande (2020).

Based on our empirical research study, we first inferred an expansive normative structure of open science among researchers working on sustainability, including institutional goal, norms, and practices enabled by the active use of digital technologies and tools and open physical and digital infrastructure. We synthesized the responsible, social, and sustainable goal – an expansive institutional goal – of open science in the digital era as informed and extended knowledge co-creation. We also distinguished a subset of expansive norms that address openness in the sharing of knowledge in open science in relation to the transparency (what is shared) and accessibility (with whom science is shared) of science outputs. We further distinguished a second subset of norms that focus on the openness in the production of knowledge in open science: authorization (how science is created and executed) and participation (where science is created).

Second, we found that open data practice is the major open sharing practice adopted by research teams when combating climate change and its impacts. We found that inbound open data access and use have become a cornerstone practice, allowing research teams to accelerate, reduce costs, and increase the relevance of their research. We observed that outbound data sharing has enabled responsible, inclusive, and sustainable research and has increased the dissemination of raw data within academia and society; this has allowed research teams to guarantee the future accessibility and usability of their work. We found that data sharing is becoming a central inducing mechanism for knowledge transfer in the digital era. We identified the challenge of quality assurance demands for inbound open data access and the challenge of opening up sensitive data sets to outbound data sharing, especially with qualitative data.

Third, we found that transdisciplinary research practice is a major open inviting practice adopted by research teams when combating climate change and its impacts. We found that research teams' transdisciplinary research practices have enlarged their research processes in terms of academic and societal engagement and collaboration by recognizing and including new participants in very early research phases. We found that transdisciplinary research practices have promoted more targeted science outputs and strengthened knowledge recombination when combating climate change. We identified the challenges of the silo discipline mindset and current reward systems when adopting transdisciplinary research practices in the sustainability field.

Finally, we found that researchers have been becoming increasingly entrepreneurial in their work, going beyond existing ways of doing research by being innovative and entrepreneurial in establishing knowledge co-creation activities and being explorative in knowledge value creation, circulation, and recombination work. We found that research and innovation intertwine and are happening at the same time, especially among university research teams that attest to expansive openness in sustainability research. It is this expansive openness that enables open science and open innovation to take place simultaneously. We discovered a new academic entrepreneurial ethos, expanding the role of researchers in the digital era, that encompasses three distinguishing characteristics of moral nature and guiding beliefs that drive research and innovation in sustainability at universities: the adoption of expansive norms of open science, a mindset of radical creativity, a sense of initiative and passion for exploring new innovative solutions, and the promotion of responsibility and inclusiveness as key values. The role of researchers is currently evolving from lab-desk science management towards platform-community science management, from "pure scientist" (Saarela, 2019) to academic entrepreneurs. Their activities exceed what is currently promoted, recognized, and rewarded through the existing research, innovation, and knowledge transfer mechanisms at universities. Researchers are becoming active explorers of knowledge, solutions, and processes to solve societal challenges.

3.4 Summary of findings: A change of paradigm in the institution of open science in the digital era

I synthesize the key findings of the three articles in Table 1, presenting the normative elements of the second open scientific paradigm and showing how these elements have expanded with regard to the first open scientific paradigm. Advances in the use of the new digital technologies and tools, together with new open physical and digital infrastructures for science inquiry have

expanded the openness of the institution of open science in the digital era. I present the definition, practices, norms, and goal of the institution of open science and the role of researchers in the digital era. I reveal the expansive openness of the institution of open science and the new academic entrepreneurial role of researchers in the digital era. This table illustrates how the second open scientific paradigm is articulated by researchers within the institution of open science in the digital era.

Table 1. A change of paradigm in the institution of open science in the digital era

	First Open Scientific Paradigm Key enablers: printing technology and physical infrastructures.	Second Open Scientific Paradigm Key enablers: digital technologies and open physical infrastructures.
Definition (dynamics of openness)	**Bounded openness** Sharing of knowledge.	**Expansive openness** Sharing of knowledge. Production of knowledge.
Practices (technical methods)	**Sharing practices** e.g. publishing papers in scientific journals, conferences, research visits, open demonstrations and exibitions.	**Open sharing practices** e.g. open data, open access. publishing or open protocols. **Open inviting practices** e.g. open collaborative tools, open physical labs or transdisciplinary research practices.
Norms (institutional imperatives)	**Communalism, universalism, disinterestedness, and organized scepticism (CUDOS)**	**Transparency, accessibility, authorization, and participation**
Goal (institutional goal)	**The extension of certificated knowledge**	**The expansion of informed and extended knowledge co-creation**
Role of researchers (behaviour patterns)	**Pure scientists**	**Academic entrepreneurs**

4. Discussion

In this section, based on the key findings, I discuss the theoretical implications of the inferred expansive normative structure of open science in the digital era and its practical implications in the established governance of research and innovation at universities.

4.1 Theoretical implications for research on open science

This doctoral dissertation lays the philosophical, sociological, and economic foundations of an expansive institution of open science in the digital era. The definition of open science in the digital era provides a comprehensive view of the streams of knowledge on the institution. The expansive normative structure of open science – its goal, norms, and practices – articulates the institution and provides a robust framework for its theoretical analysis in the digital era. This doctoral dissertation provides the grounds for understanding the institution of open science in the digital era.

First, this doctoral dissertation develops a definition for a common and clear understanding about the second open scientific paradigm's distinctive foundations. Open science in the digital era is "transparent and accessible knowledge that is shared and developed through collaborative networks" (Vicente-Saez and Martinez-Fuentes, 2018: pg. 434). This comprehensive definition allows for rigorous monitoring of the phenomenon and for the establishment of new theoretical models for effective research. This definition advances the discourse within the schools of thought (Fecher and Friesike, 2014) about the conceptualization and dynamics of openness in science – openness in the sharing and in the production of knowledge – in the digital era and contributes to the ongoing discussions about the cultural, ecologic, economic, sociological, and technological value of said openness: in sum, the human and sustainable value of open science in the digital era.

Second, this doctoral dissertation exposes an expansive institutional goal of open science, especially in regards to responsibility, well-being, sustainability, and social progress. The institutional goal of open science as synthesized by Merton is the "extension of certificated knowledge" (Merton, 1942 in Merton, 1973, pg. 270). Drawing on the findings, this doctoral dissertation infers that the goal of open science in the digital era has evolved to encompass the expansion of informed and extended knowledge co-creation. Recognizing this institutional goal of open science is key for understanding, defining, and managing – or articulating – the research process in the digital era.

Third, this doctoral dissertation develops a typology of the principles of openness in science in the digital era. It specifies openness as a multidimensional variable that can be measured and formulated by means of the proposed levels of transparency of science outputs, accessibility of science outputs, authorization in science production, and participation in science production. It later reveals that these principles are evolving into a set of expansive norms for openness in the sharing of knowledge: transparency and accessibility. Transparency addresses what is shared in open science. Accessibility addresses the question of with whom science is shared. Another set of expansive norms exists for openness in the production of knowledge: authorization and participation. Authorization addresses norms of openness with respect to how science is created and executed. Participation addresses the question of where science is created. These new "institutional imperatives" (Merton, 1942 in Merton, 1973, pg. 270) or cognitive norms for science inquiry – this set of expansive open science norms in the digital era – build on Mertonian norms of CUDOS but expand the ethos in science in terms of cooperation between collaborative networks of participants in research: researchers, universities, research institutes, companies, NGOs, states, municipalities, citizens, and international organizations.

Fourth, this doctoral dissertation develops a typology of open science practices, distinguishing between open sharing and inviting practices. These new "technical methods" (Merton, 1942 in Merton, 1973, pg. 270) in the digital era are radically transforming the traditional knowledge creation process – the research process. These practices seek out knowledge creation, circulation, and recombination by including collaborative networks of participants in research from very early conceptualization and design to the following research stages.

Fifth, this doctoral dissertation proposes that the new research process in sustainability research with these new open science practices seeks out informed and extended knowledge co-creation by including collaborative networks of participants in research from the very early conceptualization and design to the following research stages.

Finally, this doctoral dissertation helps identify and articulate the second open scientific paradigm in the institution of open science, one taking place in the ongoing evolving digital era in our society today. The new expansive normative structure of open science enables a "change of paradigm" (Kuhn, 1970) with regard to the previous modern or open science institution era. By informing and extending the research process to more collaborative networks of participants, including scientific, professional, and amateur users of scientific knowledge, science disciplines or theories are evolving. Researchers are recombining ideas, gathering new data, adapting new methods, and using new results from other disciplines and other participants in the sharing and production of science outputs for sustainable development. The new practices, norms, and institutional goal of open science are triggering new paradigms for co-creating scientific knowledge in the digital era.

This dissertation also provides the grounds for understanding how the institution of open science is remodelling open innovation at universities in the digital era. It identifies how expansive openness in science is shaping the established openness in innovation (revealing, selling, sourcing or acquiring [Dahlander and Gann, 2010]). The institution of open science in the digital era is shaping open innovation. The institution of open science is expanding. New open science practices are expanding not only the ethos in science, but also the ethos in innovation at universities. The boundaries between research and innovation are increasingly

diffuse. It is difficult to separate where research ends and where innovation begins. Research and innovation intertwine and happen simultaneously. This is especially true among university research teams that attest to expansive openness in sustainability research. It is this expansive openness that enables open science and open innovation to take place at the same time.

First, this doctoral dissertation identifies how emerging open science practices and principles are triggering novel open innovation practices in forerunner research teams at universities. It identifies two novel types of open innovation practices at universities: novel inbound open innovation practice, which relies on open science outputs to create products or service innovations, and novel outbound open innovation practice, which relies on the use of open science outputs to promote product and service innovation outside the university setting. These novel emerging practices at universities hold great potential to accelerate both internal (academic) and external (societal) processes of learning and creation of new knowledge, speeding up the research and innovation process for solutions for sustainable development goals, as well as society's grand challenges, and nurturing innovative and entrepreneurial people.

Second, this doctoral dissertation identifies a new academic entrepreneurial ethos with distinct norms, mindset, and values related to the simultaneous efforts to research and innovate solutions to advance sustainability and combat climate change. This new academic entrepreneurial ethos advances the role of researchers at universities (Perkmann et al., 2013) in the evolving digital era from lab-desk science management towards open digital and physical community science management – from "pure scientists" (Saarela, 2019) to new kinds of academic entrepreneurs.

Finally, this doctoral dissertation proposes an expansive model of university research and innovation led by entrepreneurial academics to guide the renewal of university governance in the digital era. This model can drive institutional change at universities. The new expansive practices and entrepreneurial ethos practiced by academics are transforming the established knowledge value creation and transfer process – the innovation process – in the digital era. Researchers have adopted open science and innovation practices with the aim of promoting informed and extended knowledge value co-creation, including knowledge value creation, circulation, and recombination among multiple participants in research (e.g., researchers, universities, research institutes, companies, NGOs, states, municipalities, citizens, and international organizations) and multiple types of value (e.g., cultural, ecological, economic, technological, societal, or a hybrid combination of the five). This emerging process in which entrepreneurial academics are engaged is referred to as "open exploration", which encompasses informed and extended knowledge value co-creation through open science and innovation practices. Open exploration is a new holistic research and innovation process at universities for advancing knowledge and developing actions, solutions, and technologies to achieve sustainable development.

In conclusion, this doctoral dissertation contributes to the broadening of the academic foundations of the philosophy, sociology, and economics of science in the digital era. This doctoral dissertation lays the foundations of a new expansive institution of open science in the digital era and the foundations of a new model of university research and innovation called open exploration.

4.2 Implications for university leaders and science and innovation policymakers

This doctoral dissertation provides novel insights and important suggestions for directions on how to advance open science and innovation policies and governance reforms at universities for a sustainable economy, society, and environment. It also provides guidance for inspiring open science recommendations, policies, programmes, and actions to enhance a sustainable world in the digital era.

First, this doctoral dissertation outlines a governance model of open science and innovation for universities in the digital era. This model provides helpful guidance on designing, setting up, and implementing open science and innovation practices at universities. In addition, the model provides guidance on practical suggestions for how to measure the progress of open science and innovation at universities. As such, this framework can help policymakers evaluate the degree of openness in universities' science and innovation. Openness is a multidimensional variable that can be measured and formulated by means of the proposed levels of transparency and accessibility of science outputs, authorization and participation in science production. This governance model can help in designing effective policies, roadmaps, and funding instruments to promote open science at universities.

Second, this doctoral dissertation proposes a new academic entrepreneurial ethos that can itself be considered an institutional model for universities working on sustainability in the digital era. The key values embraced by academic entrepreneurs – the expansive norms of open science, the mindset of radical creativity, the sense of initiative and passion for exploring new innovative solutions, and the promotion of responsibility and inclusiveness – can be viewed as the central part of the university model in the digital era.

Third, this doctoral dissertation proposes an expansive normative structure of open science that is central when designing effective university science and innovation public policies that promote the achievement of the Sustainable Development Goals established by the United Nations.

Finally, building on insights from the three articles, this doctoral dissertation proposes an open exploration policy for universities that promotes a nexus between open science and innovation at universities in the digital era. This novel policy considers the university as a holistic open science, innovation, and learning ecosystem – an open exploration ecosystem – for advancing knowledge and developing actions, solutions, and technologies in response to grand challenges. An open exploration ecosystem is based on informed and extended knowledge value co-creation, including knowledge value creation, circulation, and recombination, among multiple participants in research and multiple types of value. An open exploration policy for universities aspires for holistic and public scientific knowledge co-creation and transfer at universities for a sustainable economy, society, and environment and for enhancing a sustainable world.

This dissertation also provides ideas for developing UNESCO's open science policy for a sustainable world. The philosophical, sociological, and economic conceptualization of the normative structure of open science in the digital era, as well as its impact in the established governance of research and innovation at universities exposed in this dissertation, can support

and strengthen the development of the UNESCO recommendation[1] on open science. It can also inspire new and comprehensive regional open science recommendations (i.e., EU open science recommendation), and promote new open science national policies.

[1] The Recommendation is expected to established shared values and principles for open science across the Member States of the United Nations.

5. The future of an expansive open science

In this section, based on the discussion of the findings and their theoretical and practical implications, I present three possible building blocks for advancing the opening up of science to advance developments towards a sustainable world. The three building blocks can be used for transformation and to move from what I refer to as the technological age of the digital era towards one focused on human progress, enabled by new digital technologies and tools, and open physical and digital infrastructures: the humanist age of the digital era. My focus in this discussion is on possible reforms, redesigns and initiatives with regards to universities and policy building blocks for expansive open science that could be taken regionally and globally. I will discuss the European Union Research Area as a case of a regional building block, and the UN's role in expansive global open science.

5.1 Creating the university of the digital era

Nothing in life is to be feared, it is only to be understood.
Now is the time to understand more, so that we may fear less.
Marie Sklodowska Curie

5.1.1 Towards a new organizational structure of science disciplines

The new expansive normative structure of open science in the digital era is evolving universities' traditional organizational structure of science, basic research, applied research, and experimental development. The expansive practices, norms, and goal of the institution of open science in the digital era are expanding the openness of research fields, and with it, the standard edges of research disciplines. The overall openness of a research field varies in relation to the involvement of participants in the research field and the maturity of the research field. Expansive openness in science goes beyond the traditional borders of conventions of organising science disciplines. Openness in science in the digital era is reflected and extended in a multitude of arenas of knowledge development including basic research, applied research, humanities, experimental development, design, and art. Public universities need to acknowledge this emerging transformation in organizational structure when renewing their university research and innovation governance in the digital era. This will allow them to effectively design and promote new university career systems and research and innovation incentives.

5.1.2 Towards a new career system

The lack of direct open science reward incentives detected in research career development is keeping researchers from adopting open science practices in universities. The current tenure track system adopted increasingly by universities around the world, including by Finnish universities since the university reform in 2009, puts a strong emphasis on publications in top-tier journals, the number of publications, and the number of citations, but places little or no emphasis on the openness in the sharing and production of science outputs. As the main infrastructure of the institution of open science, public universities need to revise and update their current career systems to fully articulate the new expansive practices, norms, and goal of the institution of open science in the digital era. For instance, the new system needs to reward researchers' outputs and processes such as open data sets produced, transdisciplinarity of the methods used, science media content produced, community management in social networks, or engagement with a broad range of research participants. These activities and outputs promoted by academic entrepreneurs exceed what is currently promoted, recognized, and rewarded through the existing career system and reward incentives articulated with universities' open science policies.

5.1.3 Towards a new knowledge transfer system

University regulations and national and international laws on copyrights and patents are constraining the adoption of open science practices. In the digital era, public universities need to rethink the Bayh-Dole model widely implemented across the world in the last decades. Doing so would be in line with the ongoing transformation of the institution of open science. The Bayh-Dole model allows universities and researchers to have ownership and obtain economic benefits from their research work, which is mainly publicly funded by taxpaying citizens. In the last years, this model has been articulated through open innovation policies. It boosts collaboration with companies and research organizations such as private research labs, but highly restricts intellectual property rights in science projects through strict consortia agreements. This prevents effective maximization of the social value of science and progress of open science. As the main infrastructure of the institution of open science, taxpayer-funded public universities need to rethink their current knowledge transfer system and mechanisms to enhance a truer knowledge transfer for all society in the digital era. This would be fully in line with universitie's third mission – knowledge and technology transfer. The new expansive institution of open science in the digital era can guide this renewal. If the process of science is managed adequately, openness in science will benefit research participants. Open science practices achieve knowledge and technology transfer from the first steps of the research process by including participants in the informed and extended knowledge co-creation process.

5.2 Fostering a European Open Science Area

> The pursuit of science is confined to democracies.
> *Robert K. Merton*

Now, with nationalism and populism re-emerging across Europe, the institution of open science must continue promoting progress through knowledge, cooperation, and mutual understanding; through reason, and through informed and extended knowledge co-creation.

The grand societal challenge we are facing, COVID-19, can only be solved through new open science practices based on new standards of transparency, accessibility, authorization, and participation among all participants in doing research, contributing to research, using research, and defining problems and solutions in research. These practices can be used to ensure healthy lives and promote well-being for people of all ages. The challenge of COVID-19 daily shows that high levels of openness in the sharing and production of scientific knowledge is essential for saving lives. Open data sharing is allowing the development of tools, maps, and applications to monitor the pandemic's evolution and develop new treatments. Open protocols are allowing immediate implementation of measures to fight against the virus in hospitals and cities. Numerous citizen science projects are contributing to support home-schooling or mental well-being in times of self-isolation. The expansive institution of open science in the digital era is tackling the virus and saving lives.

The same applies to other global challenges. These include taking urgent actions to combat climate change and its impacts; sustainably manage forests; combat desertification; halt and reverse land degradation; halt biodiversity loss; conserve and sustainably use the oceans, seas, and marine resources; ensure access to affordable, reliable, sustainable, and modern energy; make cities inclusive, safe, resilient, and sustainable; ensure access to water and sanitation for all; ensuring inclusive and equitable quality education; and promoting lifelong learning opportunities for all. All these are societal grand challenges for achieving a sustainable world.

Openness founded on reason and scientific knowledge led to the firts open scientific paradigm in Europe. Openness inspired the foundations of open science in the late 16th and 17th centuries and articulated the institution during the Enlightenment. In the digital era, the European Union can lead the second open scientific paradigm by effectively articulating the new expansive institution of open science (practices, norms, and goal) through its European University Alliances (main public infrastructure for open science). The European Union is a good example of supranational collaboration for guarantying freedom, peace, and human progress based on the acknowledgement of interdependency and embracement of diversity. In this sense, the new normative structure of open science could be articulated through the development of the new European Research Area (European Commission, 2020), a naturally European Open Science Area for Research and Innovation.

The future European Open Science Area can act as a platform for implementing the new expansive open science practices and norms in universities, and for redesigning efficient national research and innovation systems in line with the new expansive institutional goal of open science. A new Area can be built based on informed and extended knowledge co-creation, in which knowledge is created, circulated, and recombined openly across all participants in European research to achieve a sustainable world.

5.3 Advancing worldwide scientific cooperation among the Member States of the United Nations

The future belongs to those who believe in the beauty of their dreams.
Eleanor Roosevelt

Peace is a collaborative human state. From 1945, when the United Nations (UN) first committed to "maintaining international peace and security" (Art.1.1, Charter of the United Nations), until today, peace has been articulated through a "peace infrastructure" for collaboration among Member States. With over 70 peace operations deployed since 1948, UN Peace Operations is the global keystone for designing, implementing, and managing collaborative peace activities among the Member States of the UN. In the digital era, the UN has the opportunity to promote peace through the new expansive institution of open science as well.

The ongoing development of the UNESCO Recommendation on Open Science is an essential step for raising awareness and inspiring new and comprehensive regional and national policies for enhancing open science globally. But UNESCO, UN's specialised agency, should go beyond to achieve an effective deployment of open science to tackle grand societal challenges. The expansive institution of open science requires neutral worldwide neutral infrastructure – the United Nations' open science infrastructure – to responsibly and sustainably increasing the standards of transparency, accessibility, authorization, participation, the levels of openness in science among all research participants of all UN Member States.

5.3.1 United Nations open science infrastructure for human progress

Inspired by the successful large-case worldwide scientific cooperative CERN and based on the ICT collaborative governance and infrastructure for UN Peace Operations, the UN could develop a truly open science infrastructure for tackling grand societal challenges through informed and extended knowledge co-creation. The challenges we face with COVID-19 or with climate change require new mechanisms of collaboration among all Member States of the United Nations, new open science practices, and a new mindset to overcome them. An open (1) digital UN open science cloud service at the worldwide level, (2) physical UN safe data storage services at the regional and national level, and (3) physical UN open science centres based on public universities' infrastructure at the local level would allow the sharing and development of open science outputs (ideas, data, methods, results) among all UN member states' research participants.

This infrastructure would promote neutral, independent, and reliable science-based institutions for all at the regional and national level, and advance openness in science – the scientific cooperation of the digital era – for tackling societal challenges among all UN Member States. Furthermore, this UN open science infrastructure would also strengthen the UN's mission declared in Art.1.1 of the Charter of the United Nations. It would therefore contribute to reinforce the maintenance of peace and security in the digital era by responsibly increasing the levels of transparency, accessibility, authorization, and participation in research among all Member States of the United Nations. This new infrastructure is a tool for building local, national, regional, and global knowledge communities and raising the welfare level of each. Open science in the digital era is the next scientific movement humanity has for achieving peaceful, free, equal, and diverse societies, for enhancing a sustainable world.

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Open Science now: A systematic literature review for an integrated definition

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ABSTRACT

Open Science is a disruptive phenomenon that is emerging around the world and especially in Europe. Open Science brings about socio-cultural and technological change, based on openness and connectivity, on how research is designed, performed, captured, and assessed. Several studies show that there is a lack of awareness about what Open Science is, mainly due to the fact that there is no formal definition of Open Science. The purpose of this paper is to build a rigorous, integrated, and up-to-date definition of the Open Science phenomenon through a systematic literature review. The resulting definition "Open Science is transparent and accessible knowledge that is shared and developed through collaborative networks" helps the scientific community, the business world, political actors, and citizens to have a common and clear understanding about what Open Science is, and stimulates an open debate about the social, economic, and human added value of this phenomenon.

1. Introduction

Open Science is a disruptive phenomenon that is emerging around the world and especially in Europe. Open Science brings about socio-cultural and technological change, based on openness and connectivity, on how research is designed, performed, captured, and assessed. Open data tools, open access platforms, open peer review methods, or public engagement activities are irreversible trends, that are impacting all scientific actors and have the potential to accelerate the research cycle.

Intergovernmental organisations across the world such as the European Commission, the European Parliament, the European Council, the Organisation for Economic Cooperation and Development (OECD), the United Nations, and the World Bank recognize the importance of Open Science to address the big societal challenges that humanity faces in the 21st century, such as climate change, public health emergencies, sustainable food production, efficient energy, or smart transport, among others.

But does the scientific community, the business world, political actors, and citizens have a common and clear understanding about what Open Science is? Several studies show that there is a lack of awareness among these stakeholders (European Commission, 2015b, 2015c), mainly due to the fact that "there is no formal definition of Open Science" (Arabito & Pitrelli, 2015; European Commission, 2015b; Kraker, Leony, Reinhardt, & Beham, 2011; OECD, 2015).

The purpose of this paper is to build a rigorous, integrated, and up-to-date definition of the Open Science phenomenon. Through a systemic literature review, the concept of Open Science is identified, conceptualised, and defined.

The article is structured hereinafter as follows. The theoretical framework is presented in Section 2. The methodology of the study is described in Section 3. The obtained results of the research carried out, the discussion of the findings and their implications, are presented in Section 4. Section 5 presents the conclusions, limitations, and future research horizons.

2. Theoretical framework

Open Science is an emerging field of research. Accordingly, a clear and comprehensive theoretical framework does not exist yet in academia.

The theoretical framework of this article is obtained, therefore, from the filtering process of studies carried out during the systematic literature review. Based on the analysis of a final database of 75 studies, 67 articles from reference journals of IsI Web of Science – Core Collection and Scopus, and 8 official publications from Intergovernmental organisations' databases (called henceforward International databases), all of which were published from 1985 (first detected study) to 2016 (last detected study). The research team concludes that Open Science is conceptualised as:

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0148-2963/

Open Science as knowledge: Bisol, Anagnostou, Capocasa, et al. (2014); Bond-Lamberty, Smith, and Bailey (2016); Brown (2009); Caulfield, Harmon, and Joly (2012); Cho and Choi (2013); Cook-Deegan (2007); Czarnitzki, Grimpe, and Pellens (2015); Czarnitzki, Grimpe, and Toole (2015); David (1998, 2004a); Davis, Larsen, and Lotz (2011); Deng (2011); De Roure, Goble, Aleksejevs, et al. (2010); European Commission (2014, 2015b, 2016); European Council (2016); Friesike, Widenmayer, Gassmann, and Schildhauer (2015); Fry, Schroeder, and den Besten (2009); Gorgolewski and Poldrack (2016); Grand, Wilkinson, Bultitude, and Winfield (2016); Grand (2015); Hampton, Anderson, Bagby, et al. (2015); Jamali, Nicholas, and Herman (2016); Jong and Slavova (2014); Langlois and Garzarelli (2008); Lasthiotakis, Kretz, and Sá (2015); Leonelli, Spichtinger, and Prainsack (2015); MacLean, Aleksic, Alexa, et al. (2015); McKiernan, Bourne, Brown, et al. (2016); Morzy (2015); Mukherjee and Stern (2009); Nelson (2003); OECD (2014, 2015); Peters (2010a, 2010b); Powell (2016); Rinaldi (2014); Robertson, Ylioja, Williamson, et al. (2014); Schmidt et al. (2016); Shibayama (2015); Stodden (2010); Szkuta and Osimo (2016); Thanos (2014); West (2008); Wolkovich, Regetz, and O'Connor (2012).

Open Science as transparent knowledge: European Commission (2015b); European Council (2016); Hampton et al. (2015); Kraker et al. (2011); Leonelli et al. (2015); Lyon (2016); Rentier (2016); Ramjoué (2015); Scheliga and Friesike (2014).

Open Science as accessible knowledge: Bisol et al. (2014); Czarnitzki, Grimpe, and Toole (2015); David (2004a); Merton (1973); Dasgupta and David (1994); De Roure et al. (2010); Ding (2011); European Commission (2014, 2015b, 2016); Grand et al. (2016); Grand (2015); Gittelman and Kogut (2003); Hampton et al. (2015); Jong and Slavova (2014); Lyon (2016); MacLean et al. (2015); Morzy (2015); Mukherjee and Stern (2009); Nelson (2003); OECD (2014, 2015); Rentier (2016); Rhoten and Powell (2007); Schmidt et al. (2016).

Open Science as shared knowledge: Bisol et al. (2014); David (1998); European Commission (2016); Grand (2015); Grand et al. (2016); Grubb and Easterbrook (2011); Labastida (2015); Lyon (2016); McKiernan et al. (2016); Robertson et al. (2014); Schmidt et al. (2016); Schroeder (2007); Wolkovich et al. (2012).

Open Science as collaborative-develop knowledge: Azmi and Alavi (2013); David (1998); Deng (2011); European Commission (2015b, 2016); Grand et al. (2016); Friesike et al. (2015); Fry et al. (2009); Hormia-Poutanen and Forsström (2016); Wolkovich et al. (2012).

3. Methodology

With the aim to build a rigorous, integrated, and up-to-date definition of Open Science, the research team designs a systematic literature review based on Booth, Papaioannou, and Sutton (2012) approach. The team undertakes four sequential steps following the Search, Appraisal, Synthesis, and Analysis (SALSA) Framework (Grant & Booth, 2009).

In order to manage efficiently the systematic literature review and to minimise the potential biases on the part of the researchers, the team adopts a review protocol based on Cochrane Collaboration's approach (Higgins & Green, 2011). The review protocol ensures that the team follows accurately the established methods.

Hence, the four sequential steps of the systematic literature review, established in the review protocol, are:

3.1. Step 1. Search - strategy for identification of studies

3.1.1. Search techniques

The team searches the term Open Science, when it appears either in the title, abstract, or keyword of the studies.

The team selects IsI Web of Science – Core Collection (Thomson Reuters) and Scopus (Elsevier) databases, due to the trans-disciplinary nature of Open Science and the impact factor of these databases. The aim is to carry out a comprehensive bibliography identification. Taking into account that evidence exists about the Open Science phenomenon outside the scientific community, the team searches studies in International databases such as the databases of: the European Union, the United Nations, the OECD and the World Bank.

3.1.2. Study selection criteria

For IsI Web of Science – Core Collection (Thomson Reuters) and Scopus (Elsevier) databases, the team includes articles, published in international peer-reviewed journals, written in English, and published between 2006 and 2016. The year of 2006 is chosen as a starting point because this is the year in which Chesbrough, Vanhaverbeke, and West (2006) published “Open Innovation. Researching at New Paradigm”. From this year on, Open Innovation begins to gain force and spur “open” and “cooperative” ideas in other fields of knowledge, science among them.

For International databases, the team includes official publications, which are outputs of research carried out by its departments/research institutes, or are publications that express a political commitment to the Open Science.

The team excludes proceeding papers, book chapters, books reviews, meeting abstracts, theses, interviews, editorial material, and articles that are not in English.

At the end of this step, each author runs a pilot test in order to contrast the adequacy of the search strategy.

3.2. Step 2. Appraisal - strategy for quality assessment of studies

For this step, the team uses Refworks for managing the identified references of the database.

In order to obtain a valid, reliable, and applicable database, first, the team verifies how many articles overlap among IsI Web of Science – Core Collection (Thomson Reuters) and Scopus (Elsevier). Second, the team conducts an abstract sift; those articles that mention the term Open Science once or twice without any relation with the area of research are excluded. Third, the team adds to the database the official publications found from the International databases. Finally, the team conducts a full-text sift, at the same time that the data is extracted. Those articles and official publications that do not meet inclusive criteria, do not provide a relevant definition of Open Science, or do not display data to support interpretations of Open Science definition (Dixon-Woods et al., 2006) are excluded.

3.3. Step 3. Synthesis - strategy for data extraction

Based on the research goals, the team designs a coding template in Google Sheet as a method of documentation, with the following coding variables: author, title, inclusion/exclusion, definition, key elements/dimensions, values/principles, results/opportunities, and results/challenges. In order to achieve an optimum level of reliability for the proposed coding template, the review team runs a pilot test with 10 random articles. After that, the team compares their coding experiences and adopts the final coding template. The final collection of articles is divided among the team in groups of 5 chronologically to be analysed and synthesised.

The qualitative approach to synthesise the data extracted is narrative (Rumrill & Fitzgerald, 2001), due to the fact that it helps to identify, explore, and interpret the data, as well as helps to present new perspectives, all of which contributes to the development in the next systematic step, of a definition of Open Science.

3.4. Step 4. Analysis - strategy for data analysis

The team decides to build a rigorous, integrated, and up-to-date

Graph 1. Identified studies.

definition of Open Science following Aristotle's method: "*A correct definition of X should give the genus* (*genos*: *kind or family*) *of X, which tells what kind of thing X is, and the differentia* (*diaphora*: *difference*) *which uniquely identifies X within that genus*" (Aristotle's Logic. Stanford Encyclopedia of Philosophy, 2015).

First, the team analyses how the Open Science phenomenon is built through a critical appraisal of the extracted data from the systematic review literature (Dixon-Woods et al., 2006) in order to obtain the "genus". Second, the team identifies the "differentias" by doing an exhaustive and textual analysis of the extracted data and by using a network justification system.

Finally, the team induces the definition of Open Science.

4. Results and discussion

The obtained results for each phase of the systematic literature review carried out are:

4.1. Results Step 1. Search – identification of studies

In this step the team searches "Open Science" whether in the title, abstract, or keyword of the studies - from 2006 to 2016. The total of identified studies in IsI Web of Science, Scopus, and International databases (European Commission, European Council, OECD, and World Bank) is shown in Graph 1.

4.2. Results Step 2. Appraisal – quality assessment of studies

Once all studies are identified, the team assess the quality of them by establishing the following criteria, articles – written in English – overlap sift – abstract sift & research outputs/political commitment – written in English. The total number of studies at the end of this step is shown in Graph 2.

The abstract sift reveals that the Open Science phenomenon is imprecise, ambiguous, and not well-defined. Authors mention the term Open Science without having a clear and common understanding about what Open Science is. The concept of Open Science is used in various ways for different purposes.

In this step, it is important to mention that during the full-text sift, the team finds that some authors cite and use Open Science definitions previous to 2006 (David, 1998, 2004a, 2004b; Dasgupta & David, 1994; Merton, 1973). For this reason, in order to recover that evidence in the final database, the team decides to extent the research field, which means repeating Step 1 and Step 2, taking into account inclusive criteria, to identify and select existing studies from 1900 to 2005.

The new search reveals (see Graph 3).

Finally, the total number of selected studies, after the full text sift, to create the final database is shown in Graph 4.

4.3. Results Step 3. Synthesis - data extraction

The team uses a final database of 75 studies (67 articles from reference journals of IsI Web of Science – Core Collection and Scopus, and 8 official publications from International databases), with 99 definitions (authors' own definition, authors who cite other authors' definitions) or approximations (induced definitions from displayed data), published from 1985 (first detected study) to 2016 (last detected study).

Due to space limitations is not possible to attach the final table with all extracted definitions and approximations, but it can be shared with anyone interested by requesting it by email to the authors of this paper.

4.4. Results Step 4. Analysis - data analysis

The team follows three sequential steps to build a rigorous, integrated, and up-to-date definition of Open Science:

4.4.1. Identification of "genus": what tells what Open Science is?

The textual analysis reveals that "knowledge" is the "genus" of Open Science.

"Knowledge" is an umbrella term used by the authors to explain what Open Science is. The word "knowledge" is used 31 significant times in 25 studies: Brown (2009); Caulfield et al. (2012); Cook-Deegan (2007); Czarnitzki, Grimpe, and Pellens (2015); Czarnitzki, Grimpe, and Toole (2015); David (1998, 2004a); Davis et al. (2011); Deng (2011); European Commission (2016); Friesike et al. (2015); Grand et al. (2016); Grand (2015)[1]; Hampton et al. (2015); Jong and Slavova (2014); Langlois and Garzarelli (2008); Leonelli et al. (2015); Mukherjee and Stern (2009); Nelson (2003); Peters (2010a, 2010b); Powell (2016); Schmidt et al. (2016); Shibayama (2015)[2]; Stodden (2010); West (2008).

Moreover, other times, authors use synonyms of knowledge, such as:

- Code, 5 significant times in 4 studies: Gorgolewski and Poldrack (2016); Hampton et al. (2015); Powell (2016); Wolkovich et al. (2012).
- Data, 27 significant times in 23 studies: Bisol et al. (2014); Caulfield et al. (2012); Cook-Deegan (2007); De Roure et al. (2010); European Commission (2014, 2015b); European Council (2016); Fry et al. (2009); Gorgolewski and Poldrack (2016); Grand et al. (2016), Grand (2015)[3]; Hampton et al. (2015); Jamali et al. (2016); Lasthiotakis et al. (2015); MacLean et al. (2015); McKiernan et al. (2016); OECD (2015); Powell (2016); Rinaldi (2014); Robertson et al. (2014)[4]; Schmidt et al. (2016)[5]; Szkuta and Osimo (2016); Thanos (2014).
- Ideas, 4 significant times in 4 studies: Grand et al. (2016); Grand (2015)[6]; Rinaldi (2014); Robertson et al. (2014).[7]
- Information, 3 significant times in 3 studies: Bond-Lamberty et al. (2016); Grand et al. (2016); European Commission (2015b).

[1] The author uses Nielsen's (2009) definition. Nielsen M. Doing science in the open. *Physics World* 22(5): 30–35. 2009.

[2] The author uses Dasgupta and David's (1994) and Merton's (1973) definitions. Merton R. K. The sociology of science: Theoretical and empirical investigations [N. W. Storer, ed.]. Chicago: University of Chicago Press, 1973.

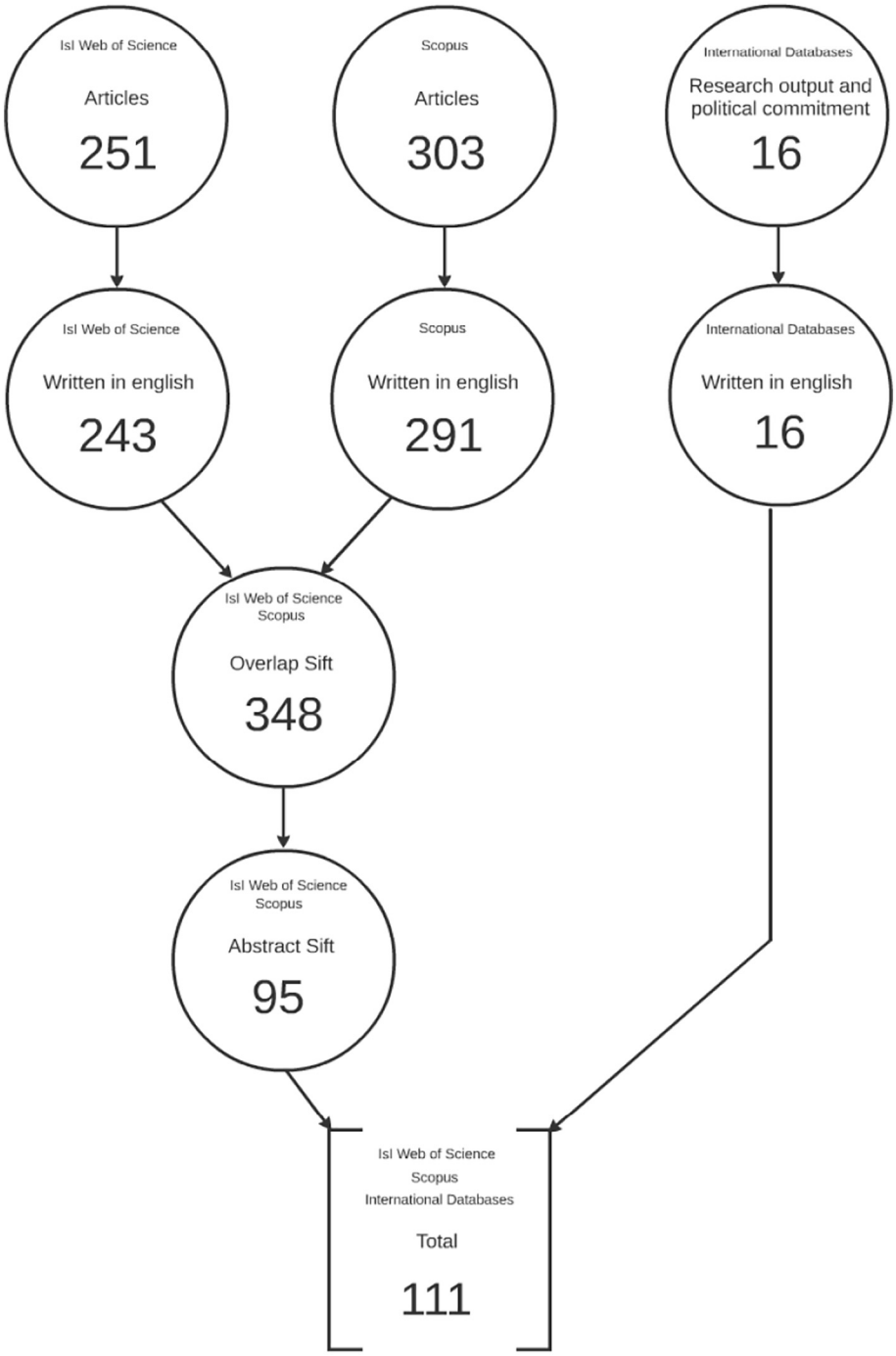
[3] Idem note 1.

[4] Idem note 1.

[5] The authors use Wikipedia's definition. https://en.wikipedia.org/wiki/Open_science

[6] Idem note 1.

[7] Idem note 1.



Graph 2. Quality assessment of identified studies.

- (Scientific) outputs, 4 significant times in 4 studies: Jamali et al. (2016); Leonelli et al. (2015); OECD (2014, 2015).
- (Scientific) publications, 10 significant times in 10 studies: Bisol et al. (2014); European Commission (2015b, 2016); European Council (2016); Gorgolewski and Poldrack (2016); Hampton et al. (2015); Jong and Slavova (2014); OECD (2014, 2015); Szkuta and Osimo (2016).
- (Scientific) results, 9 significant times in 8 studies: Cho and Choi (2013); De Roure et al. (2010); European Commission (2015b, 2016); Hampton et al. (2015); MacLean et al. (2015); Morzy (2015); OECD (2015).

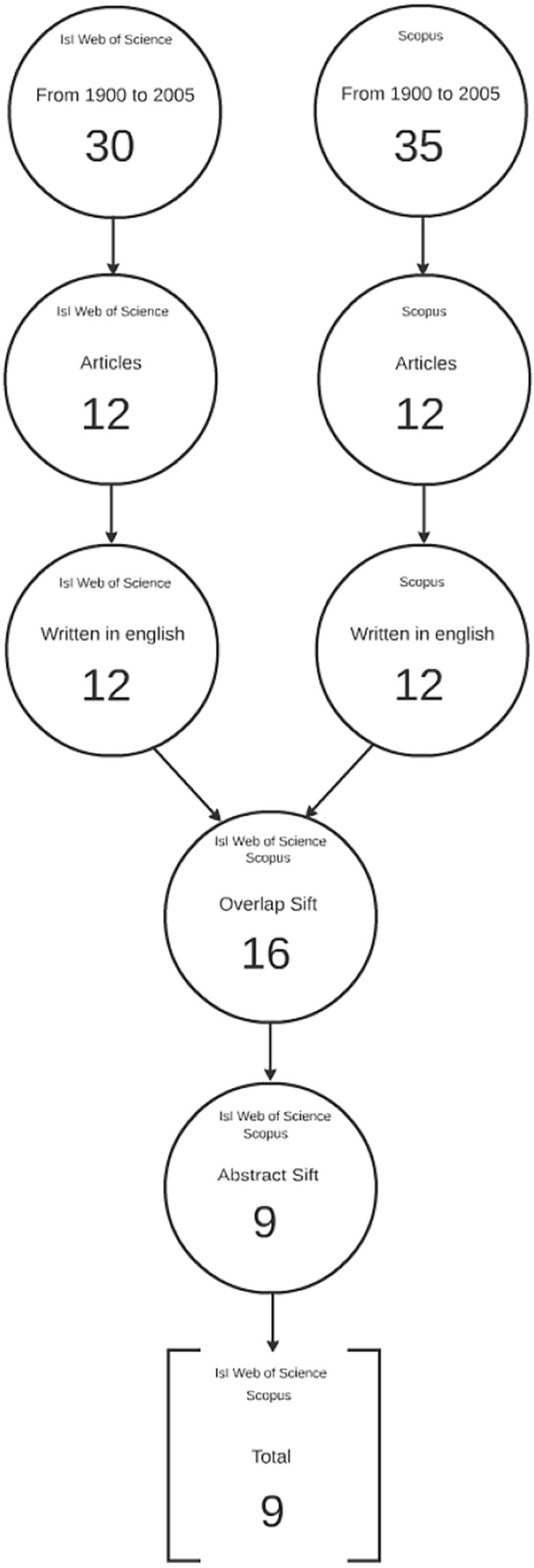
According to Aristotle's approach "*When predicate X is an essential predicate* (*it means predication in the what it is*) *of Y, but also of other things, then X is a genus* (*genos*) *of y*" (Aristotle's Logic. Standford Encyclopedia of Philosophy, 2015).

"Knowledge" is the essential predicate of Open Science, but also of other things (code, data, information, ideas, scientific results, publications, and outputs). In other words, Open Science is knowledge. Code, data, scientific outputs, results and publications, information and ideas are knowledge. Therefore, the genus of Open Science is knowledge.

4.4.2. Identification of the "differentias": what uniquely identifies Open Science within that knowledge?

The textual analysis also reveals patterns used to difference and qualify the knowledge of Open Science from other generic knowledge.

The "differentias" detected that delimit Open Science are: "transparent", "accessible", "shared", and "collaborative-developed".



Graph 3. Identification and quality assessment of studies from 1900 to 2005.

These "differentias" are used by the authors in a significant way (using the same word, or using synonyms) to characterise Open Science:

a. **Transparent**: "transparency of scientific communication" and "transparency of scientific communication" (European Commission, 2015b); "opening up of science and research", (European Council, 2016); "transparency at all stages of the research process" and "the idea that scientific knowledge should be represented in transparent and reusable formats" (Hampton et al., 2015); "opening up the research process" (Kraker et al., 2011); "transparency of knowledge production" (Leonelli et al., 2015); "a commitment and adherence to…transparency" (Lyon, 2016)[8]; "auditable research" (Lyon, 2016)[9]; "reproducibility and peer control of research" (Rentier, 2016); "opening up and democratization of science" and "making science more efficient, transparent" (Ramjoué, 2015) and "making the whole research process as transparent…as possible" (Scheliga & Friesike, 2014).

b. **Accessible**: "making publication of scientific concepts…accessible to all" (Bisol et al., 2014); "rapid public disclosure of new knowledge" (Czarnitzki, Grimpe, and Toole, 2015; David, 2004b); "disclosure of new knowledge" (David, 2004a, Merton, 1973); "results freely available on the web" (De Roure et al., 2010); "make scientific research…accessible to all levels of an inquiring society" (European Commission, 2014, 2015b); "using all available knowledge at an earlier stage in the research process" (European Commission, 2016); "making data, scientific opinions…available online" (Grand et al., 2016)[10]; (Grand, 2015)[11]; "scientific knowledge should be made freely accessible to anyone" (Hampton et al., 2015); "the disclosure of scientific discoveries" (Dasgupta & David, 1994); (Ding, 2011); (Gittelman and Kogut, 2003); (Jong & Slavova, 2014); (Mukherjee & Stern, 2009); "research made openly available" (Lyon, 2016)[12]; "results and the data of scientific research are…available to all" (MacLean et al., 2015); "making datasets publicly available" (Morzy, 2015); "depends on the disclosure of knowledge" (Mukherjee & Stern, 2009); "research is largely available for potential innovators to use" (Nelson, 2003); "scientific publications… make it available for free, or at extremely low marginal cost" (OECD, 2014); "to make the primary outputs…publicly accessible" (OECD, 2015); "full openness, searchability…research" (Rentier, 2016); "making…online research…freely accessible to a broader population" (Rhoten & Powell, 2007); "make scientific research… accessible" (Schmidt et al., 2016).[13]

c. **Shared**: "sharing important datasets" (Bisol et al., 2014); "the sharing of knowledge in regard to new findings and the methods" (David, 1998)[14]; "towards sharing and using all available knowledge" (European Commission, 2016); "the sharing of everything" (Grand, 2015)[15]; "scientific process is shared" (Grand et al., 2016); "greater sharing of the intermediate stages of research" (Grubb & Easterbrook, 2011); "new way of sharing research activities" (Labastida, 2015); "a commitment and adherence to…sharing" (Lyon, 2016)[16]; "sharing grant proposals, research protocols, and

[8] The author uses Borman (2015) definition. Borgman, C.L. *Big data, little data, no data: Scholarship in the networked world*. Cambridge, MA: MIT Press. 2015.

[9] The authors use Stodden et al. (2013) definition. Stodden, V., Bailey, D.H., Borwein, R.J., LeVeque, W.R., Rider, W., & Stein, W. *Setting the default to reproducible: Reproducibility in computational and experimental mathematics*. ICERM Workshop December 10–14, 2012, Providence. 2013.

[10] Idem note 1.

[11] Idem note 1.

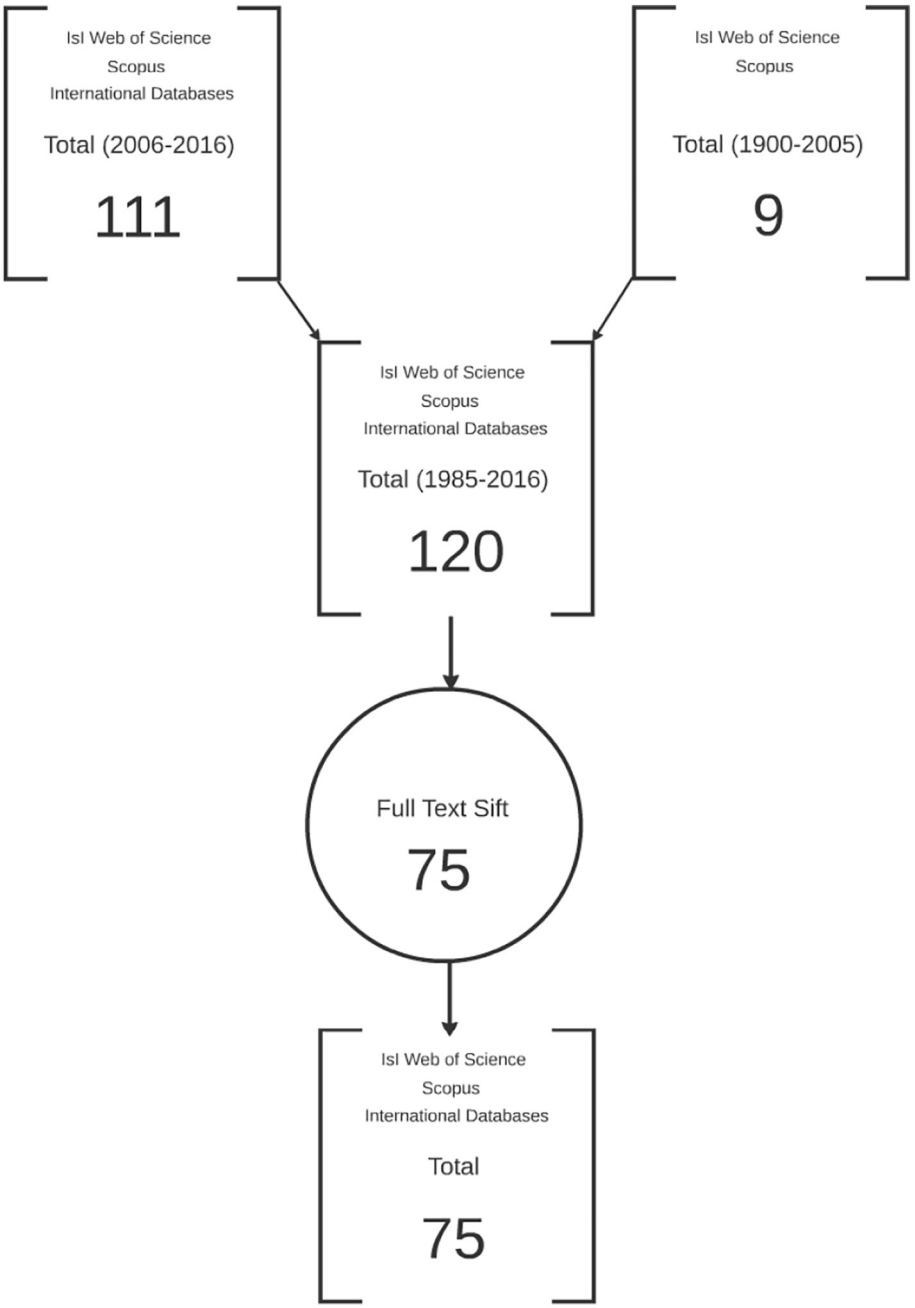
[12] Idem note 9.

[13] Idem note 5.

[14] Merton (1973, 1996 part III) definition. Merton, Robert K. The sociology of science: Theoretical and empirical investigations [N. W. Storer, ed.]. Chicago: University of Chicago Press, 1973. On social structure and science [P. Sztompka, ed.]. Chicago: University of Chicago Press, 1996.

[15] Idem note 1.

[16] Idem note 8.



Graph 4. Total number of selected studies.

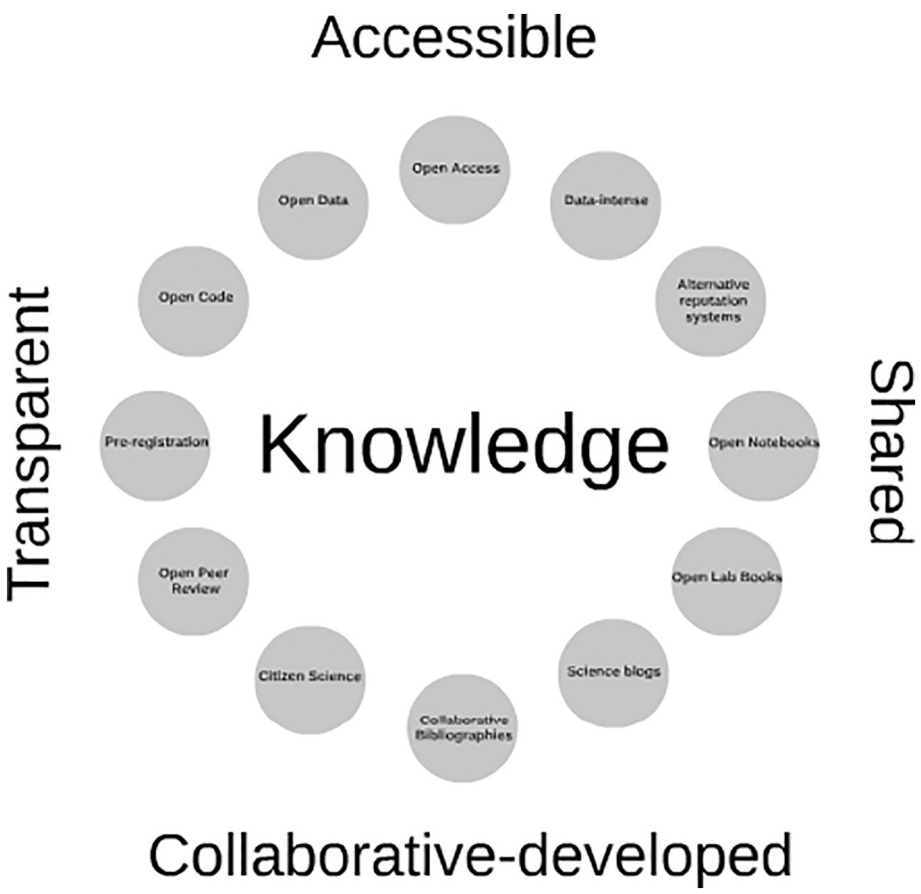
data" (McKiernan et al., 2016); "data and ideas are freely shared" (Robertson et al., 2014)[17]; "the sharing of knowledge in regard to new findings and the methods whereby they were obtained" (David, 1998; Schmidt et al., 2016); "shared among scientists or researchers" (Schroeder, 2007); "cosharing, code sharing, and idea sharing" (Wolkovich et al., 2012).

d. **Collaborative-developed**: "the cooperative character of inquiry" (Azmi & Alavi, 2013); "the cooperative character of the larger purpose" (David, 1998)[18]; "about creation….of more general human knowledge" (Deng, 2011); "the use of web-based tools to facilitate scientific collaboration" and "a novel approach to scientific development, based on cooperative work…through networks using advanced technologies and collaborative tools" (European Commission, 2015b); "based on cooperative work…by using digital technologies and new collaborative tools" (European Commission, 2016); "collaboration and dialogue" (Grand et al., 2016); "virtual knowledge creation" (Friesike et al., 2015); "science increasingly carried out through distributed global collaborations enabled by the Internet" (Fry et al., 2009); "collaboration among researchers", "collaboration across nations, disciplines and roles" and "cooperation to implement the open way of doing research" (Hormia-Poutanen & Forsström, 2016); "collaboration at numerous stages in the process" (Wolkovich et al., 2012).

4.4.3. Integration of "genus" and "differentias": proposed definition of Open Science

The research team induces the following rigorous, integrated, and up-to-date definition of Open Science by integrating the obtained "genus" and "differentias".

[17] Idem note 1.
[18] Idem note 14.



Graph 5. Open Science definition - emerging trends on Open Science.

> ***Open Science is transparent and accessible knowledge that is shared and developed through collaborative networks***

4.5. Discussion of the findings and their implications

The proposed definition of Open Science is rigorous because it is built on and draws from reliable sources including IsI Web of Science – Core Collection, Scopus, and International databases from Intergovernmental organisations across the world. In addition, it is integrated due to the fact it encompasses (Graph 5) the emerging trends on Open Science such as open code, open data, open access, data-intense, alternative reputation systems, open notebooks, open lab books, science blogs, collaborative bibliographies, citizen science, open peer review, or pre-registration. These trends share the "genus" and "differentias" of the Open Science concept, and are characterised among them by their degree of "differentias". In other words, each of them has pronounced one or more "differentias", e.g. open access: knowledge ("genus") accessible ("differentia"). Then, the proposed definition of Open Science can also help to define the trends related to the Open Science phenomenon. Finally, the definition is up-to-date inasmuch as it collects all evidence from the very start of the Open Science phenomenon, from the definitions or approximations based on the principles and values (chronological quoted) of Merton (1973); Chubin (1985); Dasgupta and David (1994); David (1998, 2004a, 2004b) to the definitions of Friesike et al. (2015); OECD (2014, 2015); Szkuta and Osimo (2016); Grand et al. (2016), Nielsen (2009); Cottey (2016); or European Commission (2015a, 2015b, 2015c, 2016), among others.

This definition helps the scientific community, the business world, political actors, and citizens to have a common and clear understanding about what Open Science is.

From the academia perspective, the proposed definition contributes to the development of a theoretical framework in the emerging field of Open Science research. The observed variables that conceptualise Open Science as "transparent knowledge", "accessible knowledge", "shared knowledge", and "collaborative-develop knowledge" can be measured and evaluated. These four dimensions allow, therefore, for the rigorous monitoring of the phenomenon and for the establishment of new theoretical models for researching effectively.

From a policy perspective, this definition contributes to the open debate on how to design and develop efficient, reliable, and useful policy recommendations, funding calls or tools that accelerate the deployment of Open Science and strengthen the research and innovation systems. In this regard, this definition may contribute to reinforcing the open dialogue of the Open Science Policy Platform, established in May 2016, on how to develop an Open Science Policy for Europe.

From a business and citizen perspective, the induced definition contributes to gain better knowledge about the opportunities and challenges that Open Science provides, especially within the field of research and innovation management: copyright, reward systems, business models, knowledge transfer mechanisms, citizen engagement, digital infrastructure, quality assurance, fair data sharing, publishing models, research and innovation funding, or evaluation of research results. This definition may stimulate business strategies, actions, and practices, in other words, new ways of collaboration that help to break down walls between Open Science and Open Innovation. Open Science can be a driver to foster responsible, sustainable, and humanist research and innovation.

5. Conclusions

The purpose of this paper is to build a rigorous, integrated, and up-

to-date description of the Open Science phenomenon. In order to obtain it, the team carries out a systemic literature review based on an interdisciplinary approach. It combines a review protocol based on the Cochrane's approach (health sciences), the SALSA framework (traditionally from the social and economic sciences), and Aristotle's method (philosophy). The induced definition "Open Science is the transparent and accessible knowledge that is shared and developed through collaborative networks" helps the scientific community, the business world, political actors, and citizens to have a common and clear understanding about what Open Science is, and stimulates an open debate about the social, economic, and human added value of this phenomenon, especially within the field of research and innovation management. This study contributes to the development of the theoretical framework in the emerging field of Open Science research. However, this study suffers from the following limitation, gathering more literature that is not in English from regions and states worldwide that have expressed commitment to the Open Science may be needed. Future research may be focused on this.

The Open Science phenomenon should be explored to understand both the opportunities and the big challenges of the 21st century that humanity has to face. In this scenario, it will be interesting to promote further research to explore the links among Open Learning, Open Science, and Open Innovation and how they contribute to the creation of a new Open Society.

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The dawn of an open exploration era: Emergent principles and practices of open science and innovation of university research teams in a digital world

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ABSTRACT

Principles and practices of open science at universities are evolving. Increasing use and application of digital technologies and platforms in research and innovation are pushing universities to take up and develop new visions and principles for how research and innovation are performed. These open science policies and practices (i.e. open data sharing, open access publishing, open repositories, open physical labs, participatory design, and transdisciplinary research platforms) are expanding the ethos of science and innovation at universities. These new principles and practices of open science at universities are also triggering novel open innovation practices by university research teams. Open science and innovation practices hold great potential for accelerating the learning and creation of new knowledge, speeding up the research and innovation process for finding solutions for grand societal challenges, and nurturing the growth of highly innovative and entrepreneurial people. The purpose of this study was to identify emergent principles, practices, and underlying mechanisms of open science and innovation developed and encountered by research teams at universities. The results of this study provide directions for how to advance openness in science at universities and illustrate how openness in innovation is being remodelled by open science practices. Based on our findings, we propose an open exploration policy and a governance model of open science and innovation at universities in the digital world, which aspire to create increased societal value.

1. Introduction

The concept of open science is spurring new visions, principles, and practices for how research and innovation are performed at universities. Open science, based on recent synthesis of research on its usage and application, aspires for "transparent and accessible knowledge that is shared and developed through collaborative networks" (Vicente–Saez and Martinez–Fuentes, 2018). Advances in digital and communication technologies and development of various types of digital platforms are nurturing new open science policies and practices in universities, such as open data sharing (Murray-Rust, 2008), open access publishing (Cribb and Sari, 2010), and participatory design. These novel open science practices have developed in tandem with novel organising forms of conducting and sharing research through open repositories, open physical labs, and transdisciplinary research platforms. Together, these novel practices and organising forms are expanding the ethos of science at universities. However, there are currently no comprehensive empirical studies on the underlying principles and practices that university research teams have developed and are using to adopt open science in response to new policies and the new digital technologies available, nor does an analysis of the factors inhibiting and enabling open science exist.

The purpose of this study was to identify emergent principles, practices, and underlying mechanisms of open science and innovation developed and encountered by research teams at universities. We studied novel practices of open science and innovation at Aalto University in Finland. We studied 15 research teams to understand what principles and practices the teams use to engage in open science, what promoting and preventing factors influence adoption of open science practices, and what practices they use to transform open science outcomes into open innovation outcomes.

The results of this study provide clarity on emergent principles and practices of open science at the universities in a digital world. Firstly, we distinguish between open sharing and inviting practices and identify

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several forms of both that have been adopted by research teams. Secondly, we clarify openness as a multidimensional variable that can be measured and formulated by levels of transparency of science outputs, accessibility to science outputs, authorization in science production, and participation in science production. Thirdly, we expose key promoting and preventing factors that influence research teams to adopt open science practices. Fourthly, we reveal two novel forms of open innovation practices developed by forerunner research teams: inbound open innovation that uses open science outputs to create product or service innovation and outbound open innovation that uses open science outputs to promote product and service innovation. As such, we provide clarity on the governance of open science and innovation at universities in a digital world and exposure to how universities are becoming active shapers and developers of novel practices of open innovation.

We end the paper with a discussion about how these new open science practices and novel open innovation practices adopted by research teams are challenging the established governance of research and innovation at universities. To undertake this endeavour, we propose a novel open exploration policy that promotes a nexus between open science and innovation at universities in a digital world.

The article is organised as follows. We present the theoretical framework on open science and innovation in Section 2. The methodology of the study is described in Section 3. The findings of the research are presented in Section 4. In Section 5, we present a discussion of the findings and their implications.

2. Theoretical framework

Open science as a phenomena is founded on two underlying mechanisms of organising science, openness (Chubin, 1985; David, 1998; David, 2004a) and connectivity (European Commission, 2016). Novel open science practices employed by research teams at universities, such as open data, open access publishing, open protocols, open physical labs, crowdsourcing practices, or transdisciplinary research platforms, are rooted in Mertonian principles of science (Merton, 1973): communalism, universalism, disinterestedness, originality, and scepticism (CUDOS norms). However, the new open science practices go beyond Merton's visions of science. Open science today centres on the aspiration for “transparent and accessible knowledge that is shared and developed through collaborative networks” (Vicente–Saez and Martinez–Fuentes, 2018). Novel open science practices and novel ways of organising science work through digital platforms, tools, and services for researchers make science increasingly accessible for citizens, knowledge freely available for everyone, scientific outputs available, and the process of knowledge creation more efficient and goal oriented (Tacke, 2010). Understanding the impact of these emerging open science practices on the “ethos of science” described by Merton, also called “norms of openness”, is a fundamental objective for ensuring the effectiveness of research systems (Chubin, 1985; David, 1998). A post-Mertonian analysis of the evolution of openness in science is therefore needed. No comprehensive studies exist, however, on the new open science practices and principles and how they could change the governance of traditional open science institutions such as universities.

Open innovation again centres on the use of purposive inflows and outflows of knowledge to accelerate internal and external innovation (adapted from Chesbrough, 2006; Chesbrough and Bogers, 2014). The open innovation phenomenon has also impacted the way universities and research teams conduct research and contribute to innovation processes (Perkmann and Walsh, 2007). Innovation is a multistage process (Baregheh et al., 2009) that incorporates multiple kinds of practices in various stages (West et al., 2014). In the last 10 years, open innovation research and policies focused on developing and promoting more inbound than outbound practices and processes for valuable knowledge creation (Enkel et al., 2009; Bogers et al., 2017). Advances in open science policies and practices such as open data (Murray-Rust, 2008), open access to research publications (Cribb and Sari, 2010), or open infrastructure for knowledge co-creation (European Commission, 2014) have disrupted established open innovation policies and, with them, the standard types of openness in innovation, that is, revealing and selling (outbound) and sourcing and acquiring (inbound) (Dahlander and Gann, 2010). Digital and communication technologies have brought about novel unexplored opportunities and challenges for the governance of innovation in universities (i.e. reliable data sharing, quality control and reproducibility of research methods and results, management of joint research platforms, funding instruments, university-industry relations, strategic alliances, spin-offs, start-ups, and consortias). In this respect, discovering how research teams use new open science outputs to shape open innovation outcomes is a priority objective for designing effective policy and governance mechanisms for universities.

Openness in science and openness in innovation are not separate constructs (McMillan et al., 2014). Open science and innovation practices at universities are constantly fuelling each other. Open science and innovation practices of universities are an emerging research field with multiple levels of analysis needed to further develop them in various scholarly communities. These practices allow the public at large to participate in contributing to research and innovation, evaluating research, increasing scientific integrity, and understanding the value of research and innovation (Tacke, 2010; Perkmann et al., 2013; Perkmann and West, 2014). Understanding how these practices impact the governance of research and innovation at universities is therefore required. The traditional institutions of open science (David, 2004a) and the novel institutions of open innovation (Chesbrough, 2015) need to be tailored, updated, and merged to reach their full research and innovation potential effectively in a digital world. Universities are firm foundations of open science and innovation practices (Bedford et al., 2018; Ayris et al., 2018) that foster innovation processes at the global, regional, national, and local level.

3. Methodology and data

We conducted a qualitative empirical research study (Gephart, 2004), taking a ground theory methodological approach (Glaser and Strauss, 1967; Corbin and Strauss, 1990; Corbin and Strauss 2008) with the aim of achieving a thorough understanding of novel and emergent open science and innovation principles and practices that research teams have developed and the underlying mechanisms that enable them to flourish or constrain them.

3.1. Research teams studied

We studied research teams at Aalto University in Finland. Aalto University serves as an exemplary site to study developing open science and innovation practices in a digital world. Aalto University was established in 2010 as a merger between three universities in the capital region: a technical university, a business school, and an art and design university. One of the key rationales behind the merger was the promotion of new multidisciplinary research and innovation practices between science, business, and industrial design researchers, practices that embrace openness in science and innovation. The vision was, through interdisciplinary and action-oriented approaches, to develop university practices in solving societal challenges (Aalto University Strategy, 2015). Furthermore, Aalto University is part of a visionary society. Finland aspires to be among the world's leading knowledge-intensive, expertise-based societies by 2025 (UNIFI, 2017) and renowned for its top education system (Economist Intelligence Unit for Pearson, 2014), being a strong innovation leader (European Innovation Scoreboard, 2018; Cornell University, 2018), and being committed to further advancement of open science in its national research system (Tuomin, 2016).

We studied 15 research teams to understand the principles and

Table. 1
Research team leaders, policymakers and university managers interviewed

Name	Position
University managers	
Anne Sunnika	Head of Open Science and ACRIS at Aalto University
Tomi Kauppinen	Head of Aalto Online Learning
Kalevi Ekman	Professor and Director of Aalto Design Factory
Policymakers	
Sami Niinimäki	Senior Adviser, Finnish Open Science and Research Initiative, Finnish Ministry of Education and Culture
Jyrki Hakappää	Senior Science Adviser, Strategic Research Unit, Academy of Finland
Sellina Päällysaho	Representative of Finnish universities of applied sciences in the Finnish Open Science Research Initiative
Research team leaders	Name of research team and School
Riikka Puurunen	Catalysis, School of Chemical Engineering
Teemu Leinonen	Learning Environments, School of Arts, Design and Architecture
Filip Tuomisto	Antimatter and Nuclear Engineering, School of Science
Pirjo Kääriäinen	CHEMARTS, School of Chemical Engineering & School of Arts, Design and Architecture
Ilkka Lakaniemi	Center for Knowledge and Innovation Research, School of Business
Virpi Tuunainen	Information Systems Science, School of Business
Ahti Salo	Systems Analysis Laboratory, School of Science
Riitta Smeds	SimLab, School of Science
Martti Mäntylä	Enterprise Systems, School of Science
Minna Halme	Aalto Sustainability Hub, School of Business
Paul Lillrank	Healthcare Engineering and Management, School of Science
Joni Tammi	Metsähovi Astronomical Radio Observatory, School of Electrical Engineering
Raimo Sepponen	Health Technology, School of Electrical Engineering
Orlando Rojas	Bio-Based Colloids and Materials, School of Chemical Engineering
Marika Hellman	BIOFILIA: Base for Biological Arts, School of Arts, Design and Architecture

practices they use to engage in open science, what promoting and preventing factors and mechanisms influence these research teams to adopt open science practices, and what practices the teams use to transform open science outputs into open innovation outcomes. Our sample was selected together with the managers of open science and innovation practices at the university. Additionally, some research team leaders suggested interviewing other research groups that we then also included. Our selection criteria included research groups from the disciplines of science, business, and art and design; groups that had engaged in multidisciplinary research; and groups that had to some degree been forerunners or active in either or both open science and open innovation activities (see Table 1). Systematic and comprehensive sampling enables better generalization, predictive capacity, and accuracy (Corbin and Strauss, 1990).

3.2. Data collection

We conducted 21 semi-structured interviews, including interviews of all the 15 research team leaders. In addition, we interviewed three managers of open science and innovation at the university and three Finnish education, research, and innovation policymakers to reinforce research reliability and better understand the context at Aalto University. In addition, these informants helped us to further understand the university's policies and practices in open science and innovation, as well as the Finnish setting of open science and innovation policies and regulations. The interviews took, on average, an hour. Moreover, we had several informal conversations with team members of the research groups when we visited the groups.

We developed an interview protocol to guide the interviews (see Appendix 1). The interview questions were open ended and aimed at understanding open science and open innovation from the points of view of the knowledgeable research team leaders, the managers, and the policymakers we interviewed. We also specifically asked for open science and open innovation practices they were engaged in or had developed without exactly defining the concept of open science and innovation itself, maintaining insight and understanding developed from the interviews and understanding of the interviewees' perspectives. We tested the interview protocol with faculty and doctoral students at the respective departments of the authors, and we refined the protocol based on the piloting and feedback from our test group. We then conducted face-to-face interviews from November 2017 to January 2018. All interviews were recorded and transcribed.

In addition to the primary data of semi-structured interviews, we collected secondary data from various sources at every phase of the research, using a variety of methods to guide sampling and ensure research validity by means of triangulation (Tracy, 2010). We carried out direct observation of research teams when we visited their sites, and we made videos and took photos of the research teams. We developed research-directed diaries to document insights from meetings and seminars attended at Aalto University during the study period. We also collected Web-based material on the research groups, university guidelines, background documents, and background archival documents on open science and open innovation policies in Finland and Europe.

3.3. Data coding and analysis

We then performed data analysis based on the grounded theory approach by Corbin and Strauss (Corbin and Strauss, 1990, Corbin and Strauss, 2008) with our primary data of semi-structured interviews. The main focus of the approach was to develop a rigorous and robust understanding of the emerging phenomenon studied. Before the iterative analysis, we carefully familiarised ourselves with the secondary data to enrich and deepen our analysis of the primary data and the phenomena of open science and innovation practices and their contexts (Suddaby, 2006). We then started, by first reading the transcripts of the interviews, to become acquainted with the data. In the second phase of our analysis, we performed open coding by assigning codes to data fragments until we reached data saturation. Through the use of questioning and the constant comparative method, we obtained an initial list of codes of open science and innovation practices that the research groups had taken up, as well as preventing and promoting factors of open science practices. In the third phase, we conducted axial coding to identify a list of coherent, consistent, and distinctive categories. We refined the previous coding scheme by constantly comparing data fragments to determine similarities and differences and establish relationships between them. We then provided a detailed description of categories of open science and innovation practices and promoting and preventing factors. Finally, we completed the data analysis by doing selective coding until we reached theoretical saturation. We then transformed our data into core concepts and determined core categories and reassembled them to propose a grounded, rigorous, useful, and comprehensive conceptual model for the governance of open science and innovation at universities. To support the progression of the analysis, we used memo writing as a tool for recording analytical insights across all data segmentation processes and the storyline technique as a mechanism for integrating and drawing concepts and presenting an overview of the studied phenomenon (Birks and Mills, 2015).

4. Findings

Our findings can be synthesised into a conceptual model for the governance of open science and innovation at universities in a digital world (Figure 1). The model distinguishes four key principles of open

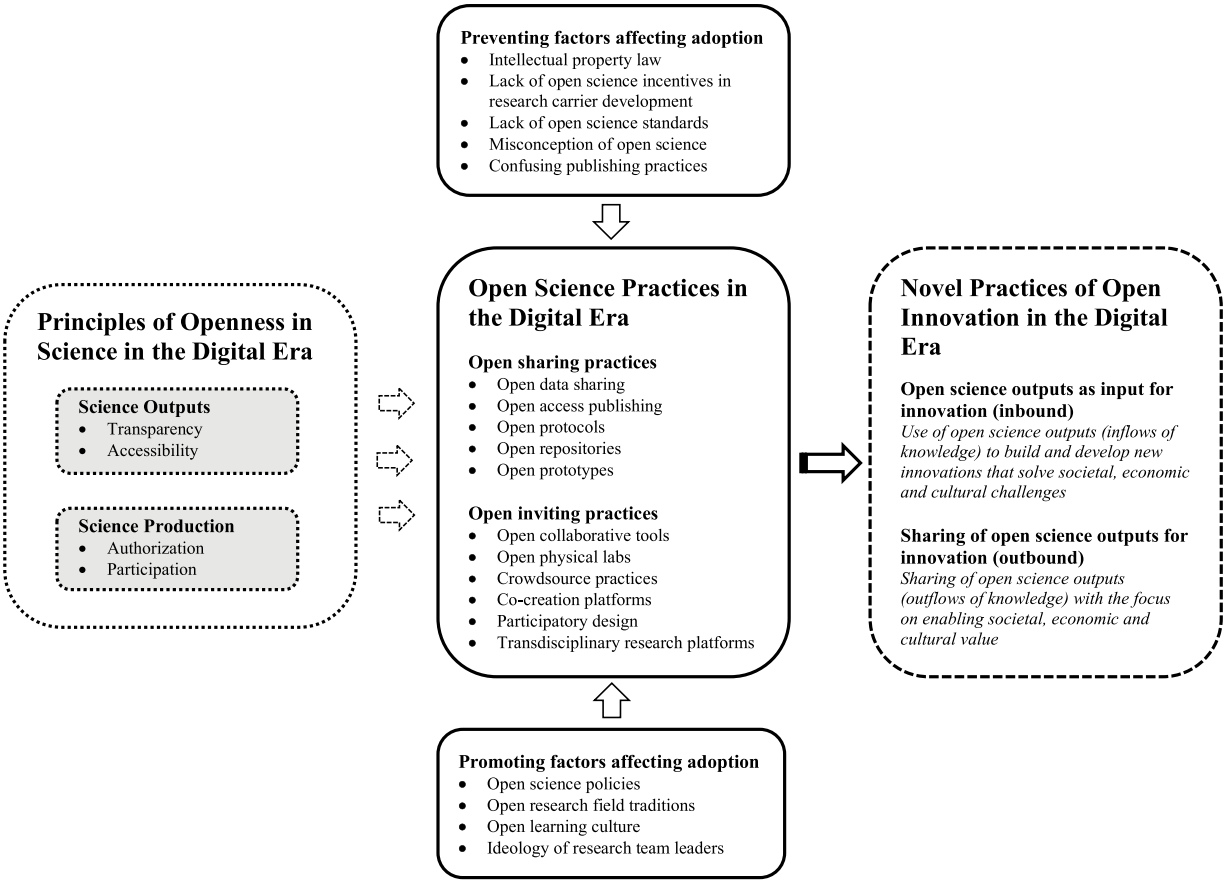

Figure. 1. A conceptual model for the governance of open science and innovation at universities in a digital world

science in the digital era that direct the work of research teams at universities: transparency and accessibility to science outputs, and authorization and participation in science production. These principles underlie the observed open sharing and open inviting practices that our research team informants had developed or were engaged in. Our study further exposes promoting and preventing factors for the open science practices to develop. Finally, our study exposes how new open science practices are triggering novel open innovation practices in universities: inbound and outbound product and service innovations. We next go through each of the elements in the model in more detail.

4.1. Open science practices in research teams

Open science practices are impacting the way research teams collect and evaluate data and design and perform scientific studies. Through our study, we identified two distinct types of open science practices in research teams: open sharing practices and open inviting practices (see Table 2).

We conceptualized the first set of practices we identified as open sharing practices. The research teams we studied exposed a variety of open sharing practices. We found that teams had practices to share data, protocols, and prototypes. An illustrative example of such practices was given by Joni Tammi, head of the Metsähovi Astronomical Radio Observatory, who explained that "the data transfer and the methods [the research group shares] are used now by more than half of the radio observatories in Europe, and soon in every observatory in Europe, as well as around the world". Many of the teams we studied had furthermore established practices to share their results and their scientific knowledge through open repositories. ArXiv, World Economic Forum, Bank of Finland, and AVAA repositories are accessible to global, regional, national, or local communities. Open sharing practices have also had an impact on the research teams' internal working. Our informants explained how the open sharing practices – open data, open access publishing, open protocols, open repositories, and open prototypes through open license practices – had accelerated the research cycle of their teams by enabling testing and recombining the scientific outputs of other scientific communities. Virpi Tuunainen, research team leader of the Information Systems Science Group, gave her summation of the value of open sharing: "Open publishing is certainly something that, not only as an idea or philosophy, is something that supports cumulative knowledge creation". All of the open sharing practices we identified that the research teams were engaged in were oriented towards spreading novel scientific knowledge in society. What is distinctive about these is that they each use non-human knowledge infrastructure that is formed using information and communication

Table. 2
Open science practices in research teams

Type of Open Science Practice	Open Science Practices
Open sharing practices	Open data sharing
Features non-human infrastructure for distributing knowledge	Open access publishing
	Sharing of open protocols
	Open repositories
	Sharing of open prototypes through open licenses
Open inviting practices	Open collaborative tools (e.g. APIS and social networks)
Features human infrastructure for creating knowledge	Open physical labs
	Crowdsource practices (e.g. citizen science)
	Co-creation platforms
	Participatory design
	Transdisciplinary research platforms

technologies.

A second set of open science practices we identified were open inviting practices. In contrast to the open sharing practices, these practices are oriented towards attracting individuals, other researchers and groups, and society to participate widely in research and to create new scientific knowledge. These inviting practices take forms such as small clubs, different sizes of consortia, and broader communities. Researchers are also increasingly engaging in practices that provide crowds with authority in research. We also found that these inviting practices of research groups vary with respect to who is invited in the development activities of new scientific knowledge, from local actors to national, regional, or global stakeholders. For example, Teemu Leinonen, research team leader of the Learning Environments Group, explained how the team he leads is looking for possibilities to improve online collaboration and online discussions by capturing the emotions of people through imaging biomarkers and computer vision. The team is learning people's emotional states through online forums or chats. This development to improve open learning environments involves global participation. What we saw from the multiple examples of inviting practices of research teams at Aalto University was that open collaborative tools, open physical labs, crowdsourcing practices, co-creation platforms, participatory design, and transdisciplinary research platforms enable the weaving of human knowledge networks, creating fertile ground for new ideas and discoveries. To summarize, open inviting practices, in contrast to non-human sharing practices, foster human interaction in science and can as such be considered the human infrastructure for creating new scientific knowledge.

4.2. The four principles of openness in science

The identification of multiple open science practices and two general types further led us to notice how the practices varied with respect to openness in multiple distinct ways in the 15 research teams we studied. Through our study, we found that openness in science is a multidimensional variable that varies with respect to four dimensions or principles: (1) transparency of science outputs, (2) accessibility to science outputs, (3) authorization in science production, and (4) participation in science production (see Table 3). Each of the principles of openness in science responds to a distinct question in relation to open science. Finally, it is important to note that any open science practice encompasses the four principles and varies with respect to the levels of openness. We next go through each of the principles of openness in more detail.

What is shared in open science? We distinguish four stages in science with respect to the outputs that can be shared: ideas, data, methods, and results. Transparency of science outputs then varies with respect to whether one or several types of output are shared. For example, Ahti Salo, research team leader of the Systems Analysis Laboratory, explained how the outcomes of his team's research, including algorithms, are “uploaded into [globally open] repositories, and I would say that that's one form of open science. If one develops an algorithm, and the claim is that the algorithm should be better, one should demonstrate it with tested examples from those repositories”. We found that research groups varied with respect to transparency of science outputs in their practices, with either one or several types of science output being shared, because such transparency of science outputs varies with respect to how extensively science outputs are shared in the process of science.

With whom is open science shared? Accessibility to science outputs varies in terms of who is given access to outputs. We found that accessibility varies as a result of economic and political interests, scientific scope, regulations, and cultural barriers. In our analysis, if accessibility varied among the research teams we studied, then we distinguished between local, national, regional, and global accessibility to science outputs. We found that many research teams aspired for global accessibility to scientific outputs. For example, Tammi, head of

Table 3
Four Principles of Openness in Science

Question	Principles of Openness in Science	Levels of Openness			
		Level 1	Level 2	Level 3	Level 4
WHAT is shared in open science?	**Transparency** of science outputs (ideas, data, methods, and results)	One type of science output is shared	Two types of science output are shared	Three types of science output are shared	All science outputs are shared
With **WHOM** is open science shared?	**Accessibility** to science outputs	Local accessibility(i.e. Helsinki)	National accessibility (i.e. Finland)	Regional accessibility (i.e. EU)	Global accessibility
HOW is open science created?	**Authorization** in science production (trust-based principles)	Club-based authority ($\leq$ 10 participants)	Consortium-based authority ($\leq$ 100 participants)	Community-based authority ($>$ 100 participants)	Crowd-based authority ($>$ 500 participants)
WHERE is open science created?	**Participation** in science production	Local participation (i.e. Helsinki)	National participation (i.e. Finland)	Regional participation (i.e. EU)	Global participation

the Metsähovi Astronomical Radio Observatory, explained, “We try to make our data completely available or as available as possible”.

How is open science created? Authorization in science production is considered a movement from the paradigm of openness (open innovation) in terms of confidentiality principles to the openness (open science) expressed by trust-based principles (authority). Researchers trust different research stakeholders to create scientific knowledge by using novel mechanisms of “intellectual trust” (e.g. crowd authority). We identified four categories of authorization among the research teams we studied: club-, consortium-, community- and crowd-based authority. For example, Riikka Puurunen, research team leader of the Catalysis Group, explained how they “have submitted one joint publication with 62 co-authors”. This exemplifies open science practices that allow intellectual trust to be established (consortium-based authority) and joint production among and between public and private actors.

Where is open science created? Participation in science production addresses where rather than how science is created. We found that research teams have opened their research labs, created collaborative research platforms, and opened up the research process to crowds (citizen science platforms). This allows for participation in the creation of scientific knowledge by stakeholders distributed across geographic areas. We found that participation in open science production varies from local to national, regional, and global participation. Several of the research teams reported an emphasis on increasingly global participation. Marika Hellman, head laboratory manager of BIOFILIA, explained how her lab's mode of operation “is all about collaboration across the world with other bio art laboratories, societies, artists, biohackers”. In addition, she noted that “BIOFILIA is a workshop space where anyone within the Aalto community could come and do projects with living material in their research or in their learning”. She further explained how the science participation practices that the lab engages in mean that “you're just open. You share what you have, you share your ideas, you listen to other people and can find collaboration between the arts and sciences fields”.

4.3. Promoting and preventing factors for the adoption of open science practices in research teams

Our study exposes both promoting and preventing factors for open science practices to be developed in university research teams (see Table 4). We found that open science policies, open science research field traditions, the open learning culture of the research team, and research team leaders’ ideology promoted the adoption of open science practices. Furthermore, we found that intellectual property laws governing research teams (university regulation and/or national/EU laws), lack of incentives for research career development, lack of standards (regarding data governance, infrastructure, practices, publishing protocols, skills, and technical support), misconceptions of what open science entails, and confusing publishing practices have prevented the adoption of open science practices. We next review our findings with respect to each of the promoting and preventing factors in more detail.

Promoting factors for the adoption of open science practices by research teams

We found that open science policies in Finland and at Aalto University enabled the research teams studied to develop open science practices that encompass a high level of transparency regarding science outputs, a high level of accessibility to science outputs, the acceptance of novel organizing forms of trust-based authority in research projects, and a high level of participation in science production. In the last five years, European and Finnish policymakers in education, research, and innovation have developed multiple policy programs to build and nurture open ecosystems through open science and innovation policies that are already implemented in annual budget negotiations with universities. Sami Niinimäki, senior adviser on the Finnish Ministry of Education and Culture's Open Science and Research Initiative, told us that the Ministry of Education “has a funding model for higher education institutions […] for the base of these negotiations. We use the assessment of the culture of openness”. The open ecosystem policies are intended to promote a co-creation atmosphere for knowledge production between research organisations, academic institutions, companies, and citizens. They are also intended to encourage researchers to reveal and make accessible their science outputs and created knowledge by encouraging researchers to engage in open access publishing and to share their data. For example, the Academy of Finland (the main research funding agency in Finland) now asks researchers to submit data management plans as part of their research proposals. Furthermore, the European level has more policies with a focus on actively promoting interoperability among open repositories in Europe. Together, these open science policies promote the development of open science practices in university research teams.

We also detected that open research field traditions are key for the adoption of open science practices with high levels of transparency, accessibility, trust-based authority, and participation. We found that research fields that have fast testing or recombination cultures (e.g. design or BioArt) and those oriented to collaboratively explore the borders of conventions with the purpose of finding solutions that address social challenges (e.g. astronomy and sustainable materials) embrace novel open science practices more noticeably. Furthermore, many of our informants told us that fostering open science culture in a research group or a department takes time to develop. Anne Sunnika, Manager for Open Science at Aalto University, expressed to us vividly that “openness depends on people”. She continued, “It depends on in which department you are in [...], what the openness level is there. It depends on people, and it takes time. Change of culture, it takes a lot of time”.

We observed that a deeply embedded open learning culture in research teams fuels open science practices with high levels of authorization and participation in science production and creates highly innovative and entrepreneurial individuals. People, not systems, are making the change. Spearheading this change are researchers who participate in open learning courses aiming to facilitate collaboration across disciplines (e.g. Bit Bang lectures), work in open physical labs (e.g. BIOFILIA activities) or transdisciplinary research platforms (e.g. CHEMARTS at Aalto University), or apply open learning approaches and methods (i.e. experiential or experience-based learning) enabled by digital means (i.e. MOOCS) in their lectures. An example from Pirjo Kääriäinen, research team co-leader from CHEMARTS, provides insight and an open-minded perspective on how and where to find information: “What I see these young people do, what they keep on doing on the

Table. 4
Promoting and Preventing Factors for the Adoption of Open Science Practices by Research Teams

Promoting factors	Preventing factors
• Open science policies • Open research field traditions • Open learning culture of the research team • Ideology of research team leaders	• Intellectual property law in science projects with companies and other research organisations • The lack of open science incentives in research career development • The lack of open science standards: data governance, infrastructure, practices, publishing protocols, skills, and technical support • The misconception of open science • Confusing publishing practices

educational side, they keep on searching for different kinds of information in very strange places. For example, they search online for certain recipes when they want to grow bacterial cellulose".

Finally, we discovered that the ideology of the research team leader (s) played a critical enabling role in the development of open science practices. We noted that team leaders who shared a strong belief that science is a tool for progress and that science needs to be open for the public good had been most active among our informants in promoting open science practices with high levels of transparency, accessibility, trust-based authority, and participation. For these researchers, science was not an "ivory tower". These research team leaders considered science as naturally open and belonging to society. These ideas are reflected in the comments provided by Teemu Leinonen, research team leader of Learning Environments: "It's almost like an ideological decision […] It's a vision which is known from history on science and research, and it's very much kind of the idea of enlightenment".

Factors preventing the adoption of open science practices by research teams

We found that the current open innovation policy, which boosts collaboration with companies and research organisations such as private research labs, restricts intellectual property rights in science projects through strict consortia agreements. These practices, we noted, constrain the adoption of open science practices with high levels of transparency and accessibility of science outputs in research teams. Filip Tuomisto, research team leader of antimatter and nuclear engineering, highlighted that "if you work directly with companies, they are the ones who prevent adopting open science principles". University regulations and national and EU laws on copyrights and patents also restrict the transparency and accessibility of science outputs including open data, open access publishing, open protocols, and open prototypes. Sami Niinimäki of the Finnish Ministry of Education and Culture, the senior official in charge of the Finnish Open Science and Research Initiative, shared his concern with us about these restrictions: "The copyright legislation, for example, is not giving enough room to operate in a fully open way as quickly as possible. It's leaning too much towards the contract model still".

We also uncovered a lack of open science incentives in research career development keeping research teams from adopting science practices with high levels of transparency, accessibility, trust-based authority, and participation. Our informants explained that researchers do not value openness in science practices when there are no direct incentives to increase transparency, accessibility, trust-based authority, or participation before publication. The current tenure track system adopted by many universities around the world – and by many Finnish universities since the 2009 university reform – puts a strong emphasis on publications in top-tier journals, the number of publications, and the number of citations, but places little emphasis on the openness of science outputs. The current carrier incentive system clearly constrains the adoption of open science practices. As Minna Halme, research team leader of the Aalto Sustainability Hub, expressed to us, "You basically proceed on your career through your publications […] This is not a problem for me any longer because I'm a tenured professor, but it's obviously a problem for any junior academics who want to go more the open-science way".

Open science is an emerging phenomenon. Several of our informants told us that because of that, open science has only recently been on the policy agenda in higher education. Unfortunately, a lack of established open science standards at the national, European, and global levels continues to persist. There is a lack of established, widely accepted standards and publishing protocols (e.g. no single standard as to how long the embargo period should last); data governance (e.g. access to data and practical processes and how to make decisions on that); and e-infrastructure interoperability and tools (e.g. the lack of "good-enough" services). Our informants suggested that this could be due to the lack of open science role model practices, few training courses for researchers about open science and open science practices, and few resources and lack of technical support capabilities at universities. Jyrki Hakäpää, senior science adviser in the Strategic Research Unit of the Academy of Finland, explained to us that "people don't know how to do [open science]", and continued, suggesting that "universities should have services and support for scholars showing and giving them examples on how to do it".

We also discovered that researchers do not have a clear understanding about what open science is or the sociocultural change it will bring about in the coming years. This is partly due to open science's lack of visibility within the university, as Anne Sunnika, Manager for Open Science at Aalto University, explained to us: "I would say that Aalto [University] as an organisation engages in open science, and we say that it is important, but the evidence of how important it is, it's maybe not very visible from the researchers' point of view". However, in addition to the lack of visibility, misconceptions and narrow views on open science are rooted in universities. An illustrative example of a more constrained view on the openness of science was provided by one of the research team leaders, who explained that "the general public should not engage in reading scientific articles […] They don't get anything from reading scientific articles". The misconceptions about what open science is and why open science culture should be an aspiration do not allow researchers to visualize its potential applications and impact on society as a whole.

Lastly, we identified confusing publishing practices that hinder the adoption of open science practices with high levels of transparency and accessibility of science outputs by research teams. The high cost of open access publishing and the current classification of open access journals in rankings discourage researchers from exploring open access publishing. One of the research team leaders, explained, "It's costly […] Actually, it's easily 2000–3000 euros per paper", then continued to say, "We [have] evaluated more than 1000 journals in the JUFO rankings [the Finnish journal ranking system that is the Ministry of Education and Culture's measure of funding for universities] […] and the open science journals are not awfully good in that ranking".

4.4. Novel open innovation practices in research teams

Our study revealed that the adoption of open science practices and principles by research teams triggers novel innovation principles and practices. We found that these novel open innovation practices, which aim to transform scientific knowledge into product and service innovations, were developed by research teams that were forerunners of open science practices. Based on our study of 15 research groups, we found that 7 of them – the Center for Knowledge and Innovation Research, CHEMARTS, Enterprise Systems, Health Technology, Learning Environments, Metsähovi Astronomical Radio Observatory, and Systems Analysis Laboratory – were engaged in various novel open innovation practices. Based on the insights from interviewing the research leaders of these seven research groups, we identified two distinct types of practices.

Novel inbound open innovation practices: The use of open science outputs to create product or service innovation in research teams

We identified a novel type of inbound open innovation practice, one that is founded on the use of open science outputs to create product or service innovation in research teams at the universities. This practice centres on the use of non-human and human infrastructures as inflows of knowledge to accelerate innovation in the research team. This novel practice refers to the use of open science outputs to build and develop new applications and innovations that solve societal, economic, and cultural challenges. An illustrative example of the development of such practice comes from Joni Tammi, head of the Astronomical Radio Observatory. He explained how his research group "are developing a service where we can take the signal from our atomic clock and transfer it basically via Internet for everyone who wants to use it [...] and for that, we are using [...] some of the data transfer protocols and technical

development, technical solutions that we found from scientific literature". He further explained the process and the benefits: "We take the data or […] the blueprints, and we can make our own version of that. We would never probably do it if we would have to pay for the patents or pay for tens of thousands or hundreds of thousands of euros for the product". Raimo Sepponen, research team leader of Health Technology, provided another example when he explained how his research team "have used imaging [technologies] […] to evaluate MRI-images [from] […] data banks [with] […] MRI images having normal and pathological images so that we can see what's happening, [and] […] we have used data [electrocardiographs] from open sources for diagnosis of arrhythmias". He further explained the process to us: "There's a large amount of cases, and then you can test your solution on how it performs with those cases". He concluded that the access to open data have helped the research group to advance prototypes and innovations in diagnostics of arrhythmias. To summarize, we found that research teams have been using open science outputs as knowledge inflows to create internal product or service innovation.

Novel outbound open innovation practices: the use of open science outputs to promote product and service innovation by anyone

The other novel type of open innovation practice we identified is an outbound open innovation practice, one that is founded on the use of open science outputs to promote product and service innovation by anyone. This novel outbound open innovation practice, in contrast to the inbound approach, focuses on the use of non-human infrastructure as outflows of knowledge to accelerate external innovation. This practice refers to the refinement and sharing of open science outputs with foci of enabling societal, economic, and cultural value. We found that research teams are using open science outputs as outflows of knowledge to promote external product and service innovation. Teemu Leinonen, research team leader from Learning Environments, provided an illustrative example of this novel open innovation practice that his research team were engaged in: ". . . this open-web idea, so in a way, anybody could download the data very easily from our applications, like the LeMill, which is for building learning materials collaboratively by teachers. So, anybody could take the data from there very easily, because it's on open web, find out that who is working a lot on what kind of topics and use it as data for research. So, they end up to be like open-science platforms, too, those learning applications". Another illustrative example of novel outbound open innovation practice comes from Raimo Sepponen, research team leader of Health Technology Group. He explained to us that the auscultatory data they have collected have been made "openly available because there is a large amount of work to collect the data, and it's good then to put it openly available because then some people don't need to do all that collection and evaluation […] that really helps the development [scientific discoveries, prototypes and innovations]". However, engagement in novel outbound open innovation practice has also raised concerns among research team leaders. Our informants expressed similar concerns about the difficulty to identify and control who use the data, methods and other science outputs they have shared: "I know that those auscultatory recordings have been used. I don't know which firms or which groups but that has been used" and "But I can see the connection. I can see that something we did 15 years ago is now in the market or is coming up with the start-ups. But I can't track back how it did end up in there. Of course, because we've been working with the open-science, so it's been available for everybody". As such, the observed novel open innovation practices are still at an emergent stage and the principles of exploitation are consequently also still up for development and debate.

5. Discussion and implications

From the Enlightenment era, when the norms and practices of open science were articulated (David, 2004a), until today, openness in science has continued to evolve in accordance with the economic, political, sociocultural, and technological constructs of each period. Digital technologies, including software, data, and hardware, communication technologies, and the development of various types of digital platforms have come to disrupt how science can be shared and collaboratively performed around the world. Digital technology enables the sharing and performing of science instantly and interactively. These technologies are as such spurring new open science principles and practices by research teams of universities; that generates new possibilities for collaboration among researchers, but also new forms of interaction between university researchers and research institutes, companies, municipalities, citizens and international organisations (e.g. the United Nations, World Bank, and European Commission).

While the policies, debates, and actions at national, regional, and worldwide levels in regards to openness in science still seem to revolve around "sharing science outputs" through open data and open access, there has already been a considerable shift in the mind set of researchers towards bringing about more openness across the entire research cycle (Plutchak, 2018) by university research teams taking up and developing novel types of open science and innovation practices. Scientific communities already use open sharing practices including open protocols, open data sharing or open repositories, and open inviting practices – that is, open physical labs, participatory design or transdisciplinary research platforms, for "co-creating science".

The results of this empirical study of 15 research teams provide an in-depth insight on what novel open science and innovation practices have developed and are being used today by university research teams. Our study provides a solid basis for outlining directions for how to advance openness in science in universities in a digital world. More specifically, our study contributes by firstly developing a taxonomy (Doty and Glick, 1998) of the principles of openness in science in today's digital world. We specify openness as a multidimensional variable that can be measured and formulated by means of the proposed levels of transparency of science outputs, accessibility to science outputs, authorization in science production, and participation in science production. Secondly, our study exposes open sharing and inviting practices in science adopted by research teams at universities. Thirdly, we synthesise preventing and promoting factors affecting the adoption of these open science practices. Finally, our study brings forth the central role of an open learning environment in enhancing the adoption of open science principles and practices by university research teams. The induction of open learning culture of the research team as a promoting factor, and the misunderstanding of open science as a preventing factor, reveal that an open learning environment is a contextual factor in the model.

This empirical study further reveals how openness in innovation at universities is being remodelled. The new principles of openness in science – transparency, accessibility, authorization, and participation – are shaping established openness in innovation (revealing, selling, sourcing or acquiring (Dahlander and Gann, 2010)). Our study shows how the new open science practices are triggering novel open innovation practices in forerunner research teams at universities. We identify a novel inbound open innovation practice that relies on open science outputs to create products and/or service innovations. We further identify a novel outbound open innovation practice that relies on the use of open science outputs to promote product and service innovation outside the university setting. These novel emerging practices at universities hold great potential to accelerate both internal academic and external societal processes of learning and creation of new knowledge, speeding up the research and innovation process for finding solutions for sustainable development goals and society's grand challenges, and nurturing innovative and entrepreneurial people.

Based on our findings, we assert that these new open science practices and novel open innovation practices adopted by research teams are challenging the established governance of research and innovation at universities. Such governance challenges arise in relation to reliable data sharing, quality control and reproducibility of research

methods and results, and the management of joint research platforms, university-industry relations, strategic alliances, spin-offs, start-ups, and consortias. A statement from Martti Mäntylä, professor and research team leader of the Enterprise Systems group, reflects this idea: "We now understand that it's not just about publishing results in open science, but also [about] creating the kind of institutions that will facilitate the uptake". In this new era of open science and innovation, what we term an open exploration era, universities, traditional open science institutions (David, 2004a), and novel open innovation institutions (Chesbrough, 2015) are under transformation. They must update their governance systems to respond to the new opportunities presented by digital technologies as well as demands for new principles and practices of open science and innovation in a digital world.

We suggest that this gap between the prevalent governance structures of open science and open innovation in universities and the emergent novel principles and practices of open science and innovation by university research teams can be bridged by adopting an adaptive and continuously evolving open governance model. To undertake this endeavour, we propose a novel open exploration policy that promotes a nexus between open science and innovation at universities in a digital world. An open exploration policy of universities considers the university as a holistic open science, innovation and learning ecosystem – an open exploration ecosystem – in which open science, innovation and learning practices in concert advance scientific breakthroughs and innovation in society.

An open exploration policy of universities has the potential to foster agile engagement with international organisations (e.g. United Nations, EU, OECD, and the World Bank) for developing innovative solutions for solving societal grand challenges: the ending of poverty and hunger, ensuring healthy lives and well-being for people, ensuring inclusive and equitable quality education, achieving gender equality, ensuring sustainable cities and communities, and combating climate change. Such innovative solutions include for instance communication solutions, medical solutions, humanitarian assistance, mobility solutions, energy and water solutions, and protection of civilians. An open exploration policy as such aspires for innovative solutions to grand challenges through co-creation of knowledge among researchers, research institutes, companies, states, municipalities, citizens, and international organisations.

From an academic perspective, our findings expand the Mertonian norms of open science (Merton, 1973) by specifying four principles of openness in science in a digital world. Open sharing and inviting practices not only build on Mertonian institutional imperatives of communalism, universalism, disinterestedness, and organised scepticism (CUDOS), but also advance the ethos of science in terms of scientific collaboration. Furthermore, the now-identified two novel types of open innovation practices at universities require further analysis to identify and distinguish various subtypes founded on open science practices in a digital world.

From the university leadership's perspectives, our results contribute by outlining a governance model of open science and innovation for universities in a digital world. This model provides helpful guidance on designing, setting up, and implementing open science and innovation practices at universities. In addition, our model provides guidance for practical suggestions for how to measure the progress of open science and innovation at universities. Our framework can as such help policymakers evaluate the degree of openness in science and innovation at universities. Our governance model can help in designing effective policies, roadmaps, and funding instruments to promote open science and bridge the gap between open science and open innovation at universities. For example, in the European Union, our findings and our proposed open science and innovation governance model can provide helpful guidance for advancing the European Open Science Agenda set up by the Open Policy Platform of the European Commission. On a global scale, the model can be helpful for universities that have signed the United Nations' Sustainable Development Goals Accord, and can provide guidance for promoting responsible, sustainable, and humanistic research and innovation through global knowledge co-creation as stipulated in the UN 2030 agenda.

To conclude, open science, innovation, and learning are drivers of an open, visionary, and fertile university environment that explores the borders of knowledge to create the future. Our governance model of open science and innovation and our proposed open exploration policy for research and innovation in universities aim to foster the creation of increased societal value from knowledge and an open society. This new policy is a tool for building local, national, regional, and global knowledge communities and raising the welfare level of each. We are at the dawn of an open exploration era.

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Appendix 1

Interview protocol

Question 1. Research Teams/Aalto Managers/Policymakers. Do you engage in open science?

Question 2. RT/AM/PM. What are the open science promoting factors that (you and your research team/Aalto's researchers/Finnish researchers) have adopted?

Question 3. RT/AM/PM. What are or what have been the preventing factors faced by (you and your research team/Aalto's researchers/Finnish researchers) in adopting open science practices?

Question 4. RT/AM. What are the practices that (you and your research team/Aalto's researchers) use to engage in open innovation?

PM. What are the best practices that (Finnish researchers) use to engage in open innovation?

Question 5. RT/AM/PM. Have (you and your research team/Aalto's researchers/Finnish researchers) used knowledge from open science platforms to create product or service innovations?

Question 6. RT/AM/PM. Is or have the developed scientific knowledge or practices that (you or your research team/Aalto's researchers/Finnish researchers) have contributed to in open science projects been used by other researchers or by firms to create product or service innovations?

Question 7. RT/AM/PM. Do you engage in open learning?

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Opening up science for a sustainable world

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Abstract:	New digital technologies and tools, together with evolving open physical and digital infrastructures, are remodelling science and innovation practices at universities and challenging their existing cultures, cognitive norms, missions, and policies. The purpose of this empirical study was to understand how existing and recently adopted open science practices and the underlying principles and attitudes of research teams support the advancement of knowledge and the development of actions, solutions and technologies for sustainable development. The results of this study provide novel insights to guide the advancement of open science and innovation policies at universities for a sustainable world. We infer a new expansive normative structure–practices, norms, and institutional goal–for open science and a new role of researchers in the digital era. Based on our findings, we propose an expansive model of university research and innovation to guide the renewal of university governance in the digital era.

Opening Up Science for a Sustainable World:
An Expansive Normative Structure of Open Science in the Digital Era

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KEYWORDS

Open science; open innovation; sustainability; openness; research teams; university; science policy, innovation policy.

Abstract

New digital technologies and tools, together with evolving open physical and digital infrastructures, are remodelling science and innovation practices at universities and challenging their existing cultures, cognitive norms, missions, and policies. The purpose of this empirical study was to understand how existing and recently adopted open science practices and the underlying principles and attitudes of research teams support the advancement of knowledge and the development of actions, solutions and technologies for sustainable development. The results of this study provide novel insights and important suggestions to guide the advancement of open science and innovation policies at universities for a sustainable economy, society, and environment–in sum, for a sustainable world. We infer a new expansive normative structure–practices, norms, and institutional goal–for open science and a new role of researchers in the digital era. Based on our findings, we propose an expansive model of university research and innovation to guide the renewal of university governance in the digital era.

Introduction

Open science is the science ahead. Open science in the digital era is "transparent and accessible knowledge that is shared and developed through collaborative networks" (Vicente-Saez and Martinez-Fuentes, 2018: pg. 434). The grand societal challenge we are facing with COVID-19 to ensure healthy lives and promote well-being for people of all ages can only be solved through new levels of integration, new science practices, and new mechanisms for global collaboration among all participants in research, from performing, contributing to and using research to defining problems and solutions in research. The same applies to the global challenges of ensuring inclusive and equitable quality education and promoting lifelong learning opportunities for all or taking urgent actions to combat climate change and its impacts. Forefront technological breakthroughs empowered by big data, artificial intelligence, the Internet of Things, machine learning, synthetic biology, 3D printing, blockchain, and quantum computing are producing unprecedented possibilities as well as challenges to instantly, interactively, collaboratively and responsibly perform science (Nielsen, 2011; Owen et al., 2012; Bogers et al.., 2018) that addresses society's grand challenges. These include, among others, the grand challenge of how to accomplish the urgent Sustainable Development Goals that the United Nations has set for 2030 (Wolkovich et al., 2012; Fiore et al., 2018; Global Sustainable Development Report, 2019).

Openness in science entails the principles of transparency, accessibility, authorization, and participation, which underlie science practice (Vicente-Saez et al., 2020). These principles indicate which aspects of the anatomy of open science are, in fact, open in the digital era. Examples of more recent open science practices adopted by research teams include open data, open labs, crowdsourced practices (Fecher and Friesike, 2014), and transdisciplinary research practices (OECD, 2020) to share and develop scientific knowledge among researchers, citizens, research institutes, companies, NGOs, municipalities, states and international organizations. The increase in the use of digital technologies and tools and open physical and digital infrastructures for researchers' science inquiry is enabling the transformation of the social institution of open science in the digital era. Digital technologies and tools and open physical and digital infrastructures are challenging existing science and innovation cultures, practices, cognitive norms, missions, and policies at universities. It is important to acknowledge that these technologies are also remodelling science and innovation practices at universities to develop actions, solutions and technologies for societal grand challenges.

Sustainability research is a young and transdisciplinary research field and is also a pioneer in open science and innovation practice development at universities (i.e., Tai & Robinson, 2018; Zipper et al., 2019). Through forerunner global, regional, national and local collaborative research projects and initiatives in sustainable development, researchers are testing new scientific practices. The field of sustainability research is establishing new interactions and processes among academia, citizens and policymakers (Hecker et al., 2018).

The purpose of this empirical study was to understand how existing and recently adopted open science practices and the underlying principles and attitudes of research teams support the advancement of knowledge and the development of actions, solutions and technologies for sustainable development. We also wanted to understand the challenges research teams have encountered when adopting novel open science and innovation practices. We studied 23 research teams at Aalto University in Finland from the disciplines of science, engineering, art, design, architecture, electrical engineering, and chemical engineering that perform research and innovative work that addresses the grand challenge of combating climate change and its impacts. The specific objectives of our study were to first expose how the four dimensions of openness in science–transparency, accessibility, authorization, and participation (Vicente-Saez, Gustafsson and Van den Brande, 2020)–were present and how their levels of openness were formulated in research teams working on sustainability, specifically in the area of climate change. Second, we aimed to identify commonalities as well as distinctive features in open science practices adopted by research teams working on climate change issues. Third, we analysed both the efficiencies gained and the key challenges prevalent in opening up science encountered by research teams. Finally, we aimed to identify open science practices' impact on the role of researchers and their teams when researching and developing actions, solutions and technologies for sustainable development.

The results of this study provide novel insights and important suggestions for directions on how to to guide the advancement of open science and innovation policies at universities for a sustainable economy, society, and environment–in sum, for a sustainable world. First, we infer an expansive normative structure of open science among researchers working on sustainability, including institutional goal, norms, and practices enabled by actively using digital technologies and tools and open physical and digital infrastructures. Such a structure is key for designing and fostering efficient science public policies in the digital era. Second, we reveal a major update in open science practices that has occurred in sustainability research among forerunner research teams. We identify how open data practice has radically transformed university research teams' processes of collecting, evaluating

and circulating data and designing and performing scientific studies. We also identify how transdisciplinary research practice by research teams has enlarged their research process in terms of academic and societal engagement and collaboration by recognizing and including new participants in every stage of the research process. Finally, we reveal how the new academic entrepreneurial ethos embracing open science norms and practices that we observed among many of the research teams is contributing to the evolution of the role of researchers and, with it, the traditional process of knowledge value creation and transfer–the innovation process–in the digital era. We conclude the paper with a discussion of the implications for governance of research and innovation in the digital era at universities.

The article is organized as follows. We present the theoretical framework on open science, sustainability, science public policy and university governance in Section 2. In Section 3, we describe the methodology of the study. The findings of the study are presented in Section 4. In Section 5, we present a discussion of the findings and their theoretical implications for research on open science and practical implications for university leaders and science and innovation policymakers.

2. Open science and sustainability in the digital era

The foundations of the modern or open science institution emerged with the ideals of the scientific revolutions of the late 16th and 17th centuries in Western Europe (Merton, 1938, in Merton, 1973; David, 1998). Openness founded on reason and the sharing of scientific knowledge led to the first open science paradigm. The prior development of printing technology and new physical infrastructure enabled scientists' adherence to new principles and practices for disclosing and disseminating new discoveries in scientific journals, in informal networks of correspondence, open demonstrations, and exhibitions. These new principles and practices challenged the social conventions as well as the incentive systems and organizational structures for performing science in that era (David, 2001, 2014). During this period, universities, which were medieval organizations for the professional practice and learning of knowledge, promoted reactionary academicist, which prevented the adoption of modern or open science (Redner, 1987). The openness of the first open scientific paradigm challenged the governance model, i.e., authority structure, of universities. In the evolving digital era, the increase in the use of digital technologies and tools and open physical and digital infrastructures for researchers' science inquiry is enabling the transformation of the institution of open science in the digital era. Open science has come to encompass a wider definition of "transparent and accessible

knowledge that is shared and developed through collaborative networks" (Vicente-Saez and Martinez-Fuentes, 2018). The openness of the institution of open science in the digital era goes beyond disclosing and disseminating knowledge among scientists of the first open scientific paradigm. It includes collaborative networks of participants in research (scientific, professional and amateur users of scientific knowledge) in the pursuit of both sharing and producing knowledge. Openness in science in the digital era hence follows two dynamics; openness in sharing and openness in producing knowledge (Vicente-Saez and Martinez-Fuentes, 2018). Understanding how these two dynamics of openness in science are redesigning and re-opening the open science institution's foundations is highly important for effectively articulating this social institution in the digital era while simultaneously encouraging social, economic, and human progress. Novel open science practices, *technical methods* such as open data, open protocols, participatory design, and transdisciplinary research practices are currently expanding the *institutional imperatives* that synthesize the ethos of science, the norms of openness (Merton, 1942 in Merton, 1973), to wider audiences and participants in science making (Vicente-Saez et al., 2020). Openness in science in the digital era involves the principles of transparency of science outputs, accessibility of science outputs, authorization in science production, and participation in science production (Vicente-Saez et al., 2020). Updating the *institutional goal of science*–"the extension of certified knowledge" (Merton, 1942 in Merton, 1973, pg. 270)– by understanding the interrelationship between the new open science practices and norms of openness in science in the digital era is key for designing and fostering efficient science public policies, for redesigning efficient research systems, and for guaranteeing independent and reliable science-based institutions for all.

The practices that become norms are continuously evolving, alongside researchers' role and researchable questions' nature. This process is especially notable in the research field of sustainability, particularly in relation to societal grand challenges such as combating climate change and its impacts. Sustainability research is a young and transdisciplinary research field that is also a pioneer in open science and innovation practice development at universities (i.e., Tai & Robinson, 2018; Zipper et al., 2019). Sustainability research is establishing new interactions and processes among academia, citizens and policymakers (Hecker et al., 2018). These interactions among different participants in research are opening up avenues to researchers to explore a variety of new roles and scientific practices for knowledge sharing and production (Saarela, 2019). Researchers' role in sustainability is gradually evolving to be more participative and collaborative (i.e., Tai & Robinson, 2018; Zipper et al., 2019). Sustainability and climate change are complex economic, environmental, political, sociological and technological phenomena that interweave with many issues of society and

nature (Tai & Robinson, 2018). Currently, strong and urgent societal demands seek to solve these issues by overcoming the traditional tensions of scientific openness in science-society relations (Hartley et alt., 2018), going beyond normative research agendas, promoting neutrality and objectivity, and sharing and developing new scientific knowledge. Modern or open science shaped the modern world (Daston, 2012) and, in the digital era, the open science institution has the potential to shape a sustainable world.

In the past, open science has dared to question the authority structure of scientific institutions such as universities in accordance with the economic, political, sociocultural, and technological constructs of the period (Redner, 1987). Emerging open science practices adopted by researchers in the evolving digital era are challenging universities' second mission–research–and their third mission–knowledge and technology transfer. These emergent practices are challenging ingrained science and innovation university mindsets, cognitive norms, practices, structures, and policies to engage in solving societal grand challenges, such as sustainability and climate change. On the one hand, these new open science practices are currently contributing to the evolution of the traditional knowledge creation process, the research process (Mukherjee and Stern, 2009; Lang et al., 2012; Mauser et al., 2013). Understanding how the new open science practices impact and transform the established knowledge creation process at universities is fundamental to developing open science policies in the digital era. On the other hand, these new practices and principles of openness in science are shaping openness in innovation (Vicente-Saez et al., 2020). Equally, open innovation practices and principles are shaping open science (Chesbrough, 2015; Friesike et al., 2015; Beck et al. 2020). Understanding how the new open science practices impact and transform the established knowledge value creation and transfer processes–innovation process–is key for developing new university governance models and updating their research and innovation governance mechanisms. Universities, traditional open science institutions from the Enlightenment (David, 2004), such as public research institutes, and more recent open innovation institutions (Perkmann and West, 2014), such as research partnerships, are encouraged to deconstruct their foundations (Perkmann, 2013; Smart et al., 2019). Universities need to re-examine their missions, aiming to strengthen their research and innovation capabilities by harnessing new open science practices' potential in the digital era.

3. Methodology and Data

We set out to study how and to what extent existing and recently adopted open science practices and the underlying principles of research teams at universities support the advancement and development of solutions for sustainable development. We conducted a qualitative empirical research study (Gephart, 2004; Edmondson & McManus, 2007; Bansal et al., 2018) using thematic coding and analysis (Fereday, & Muir-Cochrane, 2006; King and Brooks, 2018a) with a hybrid process of inductive and deductive analysis to analytically explore and capture the richest features of the data. Thematic analysis is a broadly used research method for studying, characterizing and finding patterns in rich data collected from individuals' "own words or actions or observable aspects of [their] life in an organization or culture" (Boyatzis, 1998) of complex phenomena (Daly et al., 1997; Fereday, & Muir-Cochrane, 2006). Studies applying thematic coding and analysis of practices have been conducted, for example, on SMEs' corporate social responsibility activities (Baden, Harwood, & Woodward, 2011), primary care trust policies and practices (Richardson et al., 2009), and strategic decision-making in IT projects (Alkhuraiji, Liu, Oderanti, & Megicks, 2016). We use the thematic coding and analysis steps outlined by King and Brooks (2018a).

We studied the practices of 23 research teams at Aalto University in Finland during 2019 from the disciplines of science, engineering, art, design, architecture, electrical engineering, and chemical engineering. All the teams we studied perform fundamental applied research and innovation work that address the grand challenge of combating climate change and its impacts – the UN's Sustainable Development Goal 13. We conducted semistructured interviews with research team leaders. We also made observations of the research teams' physical and digital work spaces, labs, and tools.

We built on the recent open science practice typology developed by Vicente-Saez, Gustafsson, and Van den Brande (2020). Hence, when analysing our qualitative data from site visits and interviews, we first performed a template analysis (King and Brooks, 2017; King et al., 2018b). Exposing similarities and differences in open science practices by research teams is important for understanding the underlying mechanisms that shape teams' open science and innovation practices at various levels, including the team and its leader, the research discipline, university governance, and national policies and programs.

3.1. Research teams studied

Finland and Aalto University are excellent locations to study the open science practices of research teams that are working on topics related to developing solutions for a sustainable future. Finland has been a forerunner in the EU in promoting open science and innovation and has recently been proactive in opening up public data and creating open research infrastructures. Finland is committed to promoting openness as a fundamental value and integrating open science practices into researchers' everyday work, as stated in the Finnish Declaration of Open Science and Research 2020-2025 (Federation of Finnish Learned Societies, 2020). Finland has a strong reputation as a country spearheading sustainable development (Kepa, 2017). Fully in line with Europe's vision and consistent with EU policies, Finland is playing an active role to implementing the 2030 UN Agenda for Sustainable Development at the national level and internationally. Accordingly, in its climate policy, Finland advocates for the implementation of the Paris Agreement and recognizes climate's social, economic and environmental dimensions to promote a carbon-neutral welfare society (Publications Prime Minister's Office, Government report on the implementation of the 2030 Agenda, 2020). In this context, the role of Finnish researchers in sustainability–such as forest bioenergy, a very polarized area with regards to carbon-neutrality and biodiversity sustainability–is gradually moving from "pure scientists" towards more "participatory knowledge producers" (Saarela, 2019).

Aalto University was able to shake off some of the institutional inertia of universities when it was funded as part of a university regulatory reform in Finland in 2010. Aalto University arose from the merger in 2010 of a business school, a technical university, and an architecture, art and design university. The current university mission, articulated in 2019, is bold. Aalto University states that its mission is to renew society with research-based knowledge, radical creativity and an entrepreneurial mindset. The university promotes the creation of novel open physical and digital spaces as well as practices that encourage breakthroughs in and across science, art, technology and business. An explorative culture is empowered in several ways, such as through internal funding, personnel allocations, and recognitions (e.g., awards). One of the key rationales for the active support an explorative culture is the goal of pioneering innovative solutions for a sustainable world (Aalto Living Strategy, 2020). Sustainable development is the "ethos" of Aalto's strategy and values. In line with Aalto's mission, the university has recently jointly founded the University Network for Innovation, Technology and Engineering (UNITE!), a European University Alliance composed of 7 European universities. UNITE! aspires to generate innovative, feasible, and effective solutions to global challenges in line with open science principles and practices (UNITE Mission Statement, 2019).

We studied 23 research teams to understand how existing and recently adopted open science practices and the underlying principles of research teams support the advancement and development of solutions for sustainable development. We explored and analysed scientific research and artistic activities conducted in the research groups at the School of Arts, Design and Architecture, School of Chemical Engineering, School of Electrical Engineering, School of Engineering, and School of Science to select our sample. We included research teams whose research focus was climate change mitigation technologies and solutions as well as research and artistic activities that contribute to raising awareness. We further ensured that the sample of 23 research teams included a representative variance of research teams with respect to the openness of their research practices with respect to the four open science dimensions (see Table 1). These selection criteria ensured richness in the observations and rigor in finding commonalities and explainable differences (Tracy, 2010). Our sample is a solid, descriptive, and scalable representation of the Finnish and EU context for the accomplishment of the 2030 UN SDGs Agenda. These research teams, comprised of small to medium size groups of early career and consolidated researchers, are neutral representatives of their area who are working on sustainability research. They are supported by university, national and international funds. The research teams are all internationally active in conducting research, contributing to research, using research, and defining problems and solutions with collaborative networks when working in topics related to combating climate change and its impacts.

Table 1. Research team leaders interviewed

Research Team Leaders	Title and Responsibility	Name of Research Team and School	Research topics
Antti Ahlava	Vice-President for Campus Development, Professor and Research Team Leader	Group X, School of Arts, Design and Architecture	Shared resources and mixed use; sustainable development; life cycle thinking; co-design; user-centered design; value co-creation; communicative planning; parametric solutions; learning organizations and spaces.
Idil Gaziulusoy	Professor and Research Team Leader	Sustainable Design Research Group (NODUS), School of Arts, Design and Architecture	Transdisciplinary research and co-creation, socio-ecological-technological system transformations; sustainability science; practice theory; self-organizing systems; participatory and collaborative design; futures studies; governance innovations.
Olli Dahl	Professor and Research Team Leader	Clean Technologies, School of Chemical Engineering	Sustainable industrial processes; treatment of waste water and industrial residues; responsible use of raw materials; development of cleantech-processes; environmental technology.
Bassam El Baroni	Professor and Head	Sharing and Cocreating Transdisciplinary Artworks Initiative (SCTA), School of Arts, Design and Architecture	Responsible exhibitions; transdisciplinary artworks; collections and public art. Climate was an open call to Aalto Community (artist, students, and researchers) to submit proposals about how food might help us to understand the impacts of climate change.
Juanjo Galán	Professor and Research Team Leader	AaltoLAND – Landscape Architecture Programme, School of Arts, Design and Architecture	Green infrastructures; ecosystem services; landscape urbanism; sustainable metabolisms; landscape characterization and assessment; the environmental, cultural, socioeconomic and sustainable dimension of the landscape.
Kamyar Hasanzadeh	Researcher and Coordinator of the Open Data Initiative	Spatial Planning and Transportation Engineering Group, School of Engineering	Engineering as collaborative development; sustainable built environment; systems design; human-centered living environments; new planning and policy-making methods and processes; development and governance or urban technologies and services.
Pekka Heikkinen	Professor and Research Team Leader	Wood Programme in Architecture and Construction, School of Arts, Design and Architecture	Construction for a sustainable future; energy efficient building design; natural building materials; wood architecture and industrial building.
Mark Hughes	Professor and Research Team Leader	Wood Material Technology, School of Chemical Engineering	Climate change mitigation potential of wood in construction; wood technology; wood in climate smart construction; wood in comfortable and healthy buildings; bio-composite materials.
Marjo Kauppinen	Professor and Research Team Leader	Product Requirements and Architecture Research Group (Preago), School of Science	Development of digital services; requirements engineering, user-centered and service design, customer value and user experience, data science as part of digital services, software ecosystems, eHealth
Jaakko Ketomäki	Professor and Research Team Leader	Smart Building Technologies and Services, School of Electrical Engineering	Smart building; sensor networks; human-building interaction; intelligent control strategies of building systems.
Harri Koivusalo	Professor and Research Team Leader	Water and Environmental Engineering, School of Engineering	Global water resource scarcity; sustainable circular economy; water and development; water resources management; environmental hydraulics; wastewater engineering.

Marketta Kyttä	Professor and Research Team Leader	Spatial Planning and Transportation Engineering, School of Engineering	Engineering as collaborative development; sustainable built environment; systems design; human-centered living environments; new planning and policy-making methods and processes; development and governance or urban technologies and services.
Jorma Kyyrä	Head of the Department of Electrical Engineering and Automation, Professor and Research Team Leader	Illumination Engineering, School of Electrical Engineering	Illumination engineering; electrical building services; indoor lighting, energy efficient lighting systems; outdoor lighting; visual and biological effects of lighting; lighting measurements and testing; LEDS and plant lighting.
Jorma Kyyrä	Head of the Department of Electrical Engineering and Automation, Professor and Research Team Leader	Industrial and Power Electronics, School of Electrical Engineering	Novel computational schemes and intelligent systems; electrical power/energy engineering; modeling hybrid-powered utility vehicles and their power converter and energy-storage units; energy-efficient (or "green") data centers; energy efficient townhouse.
Pirjo Kääriäinen	Professor and Research Team Leader	CHEMARTS, School of Chemical Engineering and School of Arts, Design and Architecture	Performance and design of advanced cellulosic materials; design driven technology development processes; future business seeds of sustainable world of materials; biomaterials; plant-based materials.
Harri Lipsanen	Professor and Research Team Leader	Nanoscience and Advanced Materials, School of Electrical Engineering	Nanomaterials; nanostructures; and advanced materials for nanoelectronics and nanophononics; graphene and related 2D materials; energy efficiency especially in advanced LED and solar cell concepts; nanofabrication by atomic layer deposition; micro-, nano- and optoelectronic devices based on semiconductors (GaN, GaAs, InP, Si...) and their nanostructures (such as quantum dots, nanowires and black silicon).
Mari Lundstrom	Professor and Research Team Leader	Hydrometallurgy and Corrosion, School of Chemical Engineering	Hydrometallurgical processing of primary and secondary raw materials; electrochemistry; secondary raw materials for the development of new processes and materials in circular economy of metals; sustainable industrial-scale process development.
Jukka Manner	Professor and Research Team Leader	Internet technologies, School of Electrical Engineering	Green ICT; evolution of routed ethernet and software defined; networking; cyber security; militar and government communication infrastructures and protocols.
Yrjö Neuvo	Research Director and Professor	Aalto Energy Platform and Energy Conversion, School of Engineering	Thermal materials and bioenergy conversion; thermodynamics; fluid mechanics and chemistry in energy technology; combustion and spray technology.
Marko Nieminen	Professor and Research Team Leader	Digital Opportunities, School of Science	Services for sustainable business in emerging markets; low-barrier digital service platform for citizens living in informal communities.

Antti Punkka	Professor in the Finnish Open Climate University Initiative	Systems Analysis Laboratory, School of Science	Mathematical theories and algorithms of optimization; control and decision making to the practical interactive computer modeling and decision support systems and risk and technology assessment; complex energy, production and environmental systems; biological modelling; systems intelligence and applied philosophy in human organizations.
Riikka Puurunen	Professor and Research Team Leader	Catalysis, School of Chemical Engineering	Sustainable catalytic processes from renewable resources; preparation of solid heterogeneous catalysts e.g. by atomic layer deposition; characterization of solid heterogeneous catalysts.
Miina Rautiainen	Professor and Research Team Leader	Geoinformatics – Remote Sensing, School of Engineering	Methods for monitoring vegetation from space; measuring and modeling the spectral and structural properties of forests; remote sensing; spectroscopy; radiative transfer modelling; laser scanning; and forest and environmental sciences.
Ahti Salo	Professor and Research Team Leader	Systems Analysis Laboratory, School of Science	Mathematical theories and algorithms of optimization; control and decision making to the practical interactive computer modeling and decision support systems and risk and technology assessment; complex energy, production and environmental systems; biological modelling; systems intelligence and applied philosophy in human organizations.
Sanna Syri	Professor and Research Team Leader	Energy Efficiency and Systems, School of Engineering	Energy generation; energy consumption system; efficient energy use and indoor climate in buildings; societal and economic impact of energy technologies; transformations of energy systems to reach carbon-neutrality.

3.2. Data collection

We conducted semistructured interviews with all 23 team leaders. In addition, we conducted 2 informal interviews with early-career team research members (Bahlai et., 2019) as validity check, which are included in Table 1. We developed an interview protocol to guide the collection of data during the interviews (see Appendix 1). To guide the development of the interview questions, we used the insights and findings of Vicente-Saez et al. (2020) on the open science and innovation practices of university research teams. The interview questions were open-ended to obtain the richest data possible to strengthen reliability in pattern identification during data analysis and to ensure methodological fit (Edmondson & McManus, 2007). We refined and validated the interview protocol with a test group of 2 professors and 3 doctoral students at the corresponding departments of the authors. The face-to-face interviews were conducted from October to December 2019. The interviews were recorded and ranged from 24 to 59 minutes. All interviews were transcribed.

In addition to the primary data of the semistructured interviews, we made observations of the research teams' digital and physical work spaces, labs, and tools. We took pictures and videos during the visits and developed a research voice memo diary to document insights from the interviews and observations. We also collected web-based material on the scientific, innovative and artistic activities of the research groups, university strategy documents, and most recent (past 10 years) central official policy documents on open science and sustainable development produced by the Ministry of Education and Culture in Finland – Open Science National Coordination (4), European Commission, DG Research and Innovation (6), OCDE (2) and United Nations (7). These secondary data, which were collected using different methods, ensured research credibility by means of triangulation (Tracy, 2010).

3.3. Data analysis

We performed data analysis with our primary data of semistructured interviews, undertaking a thematic analysis approach to organizational research (King and Brooks, 2018a) by using a template analysis style (King and Brooks, 2017; King et al., 2018b). This approach helps to ensure "credibility", "dependability", and "transferability" in qualitative studies (Polit and Beck, 2008).
First, we started the iterative data analysis by familiarizing ourselves with a subset of the data. We selected one interview from each research discipline, 5 interviews in total, and one of each of the schools of Aalto, which represented a good cross-section of the data set. Second, we conducted a

preliminary coding of these 5 interviews to start defining themes. We established four a priori themes, the four theorized dimensions of openness in science: transparency and accessibility of science outputs and authorization and participation in science production (Vicente-Saez et al., 2020). We defined the themes according to the research objectives. We used the qualitative data coding software tool Atlas.ti to assist in the process of coding and memo writing. Third, we organized all identified themes into significant clusters. We distinguished how the four theorized dimensions of openness in science (Vicente-Saez et al., 2020) were present and differed in significant ways in each research group. We also identified commonalities as well as distinctive features in the open science practices – open sharing and inviting practices - of research teams working on climate change issues. We further identified key challenges and efficiencies gained in opening up science that were encountered by the research teams. We identified the impact of open science practices on the role of researchers when researching and developing actions, solutions and technologies for sustainable development. Fourth, we developed our initial template based on the clusters of themes identified. Due to the diversity of the research disciplines and with the aim of achieving a comprehensive representation of the data, we decided to repeat steps 1, 2 and 3 by working systematically with a new subset of 5 interviews, one from each of the schools of Aalto. We met frequently as a research team to refine the template and include new themes, redefine existing themes and delete themes. Fifth, we formulated and agreed on the final template. We applied the template to the entire data set. We then recoded previous interviews. This template was the basis for performing the final analysis of the coded data and structuring our findings. Finally, we prioritized the most relevant insights considering how and to what extent existing and recently adopted open science practices and the underlying principles of research teams at universities support the advancement and development of solutions for sustainable development. In the next section we present our findings.

4. Findings

4.1. An expansive normative structure of open science in the digital era in sustainability

Through our study, we infer an expansive (i.e., marked by expansion) normative structure of open science, including a new set of open science practices, norms and institutional goal among researchers working on sustainability at universities (see Figure 1). This expansive normative structure is enabled by the active use of digital technologies and tools and open physical and digital infrastructures by research teams and their development of new scientific practices. Based on the analysis of our primary data (interviews), triangulated with our secondary data (policy documents, collected web-based material, and observations), we expose key characteristics and the operation of the new sets of norms and institutional goal for open science practice that the studied researchers embraced. The next section presents in detail our findings on the expansive normative elements of open science in the digital era in sustainability.

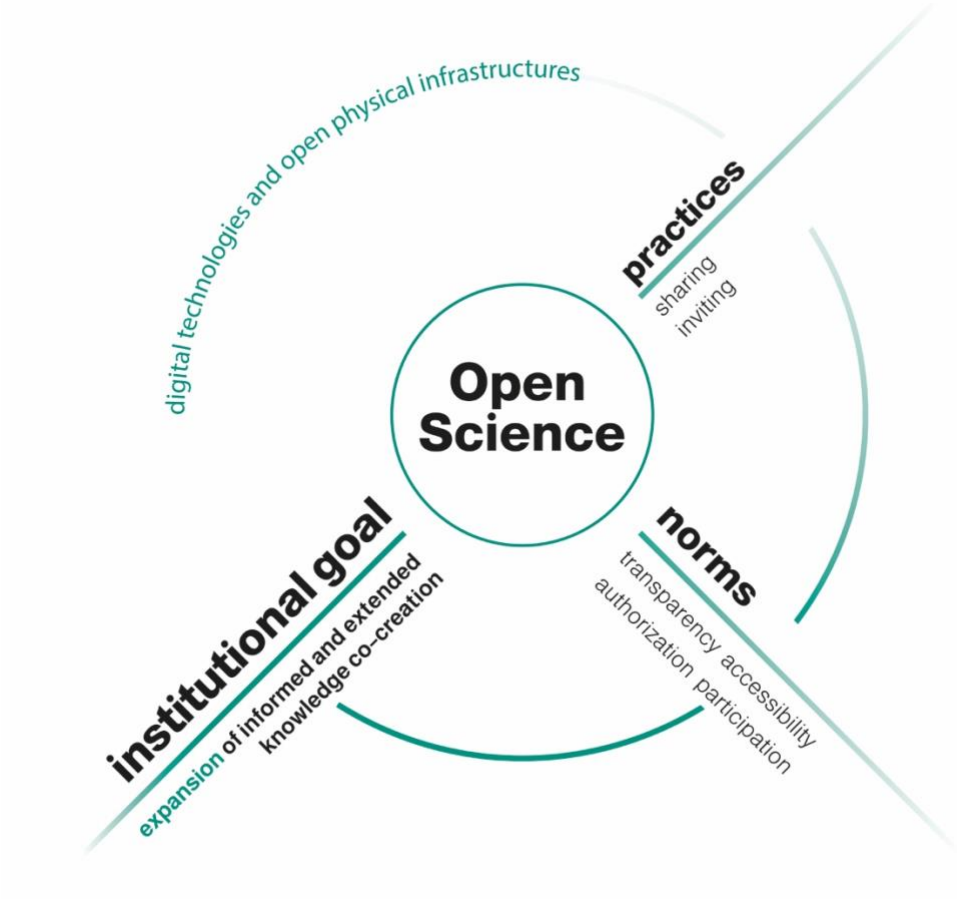

Figure 1. An expansive normative structure of open science in the digital era in sustainability

4.1.1 The expansive norms of open science

Open science norms are professional practices of proper or acceptable behaviour upheld by the values and mind sets of researchers. Among the 23 teams, we found that a majority, 19 research teams, were assigning to and embracing expansive openness norms. The leaders of the research teams explained to us that solving grand challenges such as climate change has pushed them to actively explore and adopt novel open science practices.

We found that the research teams we interviewed had all embraced novel open science practices, both open sharing and open inviting practices (Vicente-Saez et al., 2020), in multiple forms and with diverse levels of openness. The various open science practices – *technical methods* - of the research teams we documented were founded on the open science principles of transparency of science outputs, accessibility of science outputs, authorization in science production, and participation in science production (Vicente-Saez et al., 2020). With the expansive use of open science practices in sustainability research, the questions that researchers are asking have also evolved. With constantly developing open science practices, scientists' underlying principles and norms of science are also evolving.

We distinguished a subset of expansive norms that address openness in the sharing of knowledge in open science in relation to the transparency and accessibility of science outputs. Transparency addresses what is shared in open science. This includes ideas, data, methods and results that are shared in a transparent manner. A clarifying example of the expansive transparency norm in open science practice in research teams working on sustainability and climate change issues was given by Juanjo Galán, research team leader of the AaltoLand Group, who explained, *"When you're dealing with complex issues in which society is involved, you need to have a kind of high level of connection with the society, and sharing different stages of the research process is really important".* This involves *"the different stages of the research process, [including] the definition of the research problem, the definition of the research questions, and the applications of the methods"*. We also found that the teams we studied embraced an expansive norm of accessibility. Accessibility addresses the question of with whom science is shared. We found that the research teams we studied had increasingly engaged in broadening sets of local, national, regional, and global collaborative networks over the last ten years. An illustrative example of how openness is ascertained by the accessibility of science outputs was given by Idil Gaziulusov, research team leader of the Sustainable Design Group (NODUS), who noted that *"everything that we produce, every scientific output that we produce, I*

think as long as there are resources, is open. I have recently published a book, and that's also open—I mean, it's hard copy is, of course, being sold, but we paid, Aalto has paid for making the electronic version openly accessible". I: "To everyone?" R: "Everyone".

We further distinguished a second subset of norms that address openness in the production of knowledge in open science: authorization and participation. Authorization addresses norms of openness with respect to how science is created and executed. We observed that the research of the teams we studied had changed from being conducted solely by the research team to being co-produced with stakeholders. This shift in creating and executing research highlights the ability to trust participants and to equally confer trust to receive valuable inputs into the science process. The norm of authorization in science production – instilling trust in consortia's communities and crowds invited to the scientific process – has gained a central role in sustainability research. A clarifying example of this expansive norm of authorization in science production, encompassing the expansion of trust-based principles, was given by Pirjo Kääriäinen, research team leader of the CHEMARTS Group: "*My research group is about societal transformation for sustainability, which means that we have to work with societal actors (…) So we do co-create knowledge, methods, outputs with knowledge users or non-academic as well as, of course, academic stakeholders".* We also found that the teams we studied adopted an expansive norm of participation. Participation addresses the question of where science is created. We found that among the teams we studied, science production in sustainability research has expanded to co-production with a wide set of geographical networks, ranging from local, national, and regional to global collaborative networks. An illustrative example of the expansive norm of participation in science production was given by Ahti Salo, research team leader of the Systems Analysis Laboratory Group: *"So the biggest [workshops] have had some 400 stakeholders from all over Europe […][the invitation] was sent to a group of selected stakeholders rather than everyone in the world. But – I mean, the platform was open then to all who were invited"*.

4.1.2 The expansive institutional goal of open science

We found that the institutional goal of open science is expanding with regard to the norms of researchers and their teams and the new open science practices employed in sustainability research. In addition to the expansion of the norms of open science, based on our analysis of the 23 research teams, we identified an expansive institutional goal of open science, moving from the "extension of certificated knowledge" (Merton, 1973, pg. 270) to one that is focused on informed and extended knowledge co-creation in the digital era.

This expansive institutional goal arises from the interrelationship between the expansive subsets of norms of open science discussed above as well as the expansive open science practices in sustainability research in the digital era. Sharing ideas, data, methods, and results with local, national, regional, and global collaborative networks of participants in research brings to the forefront informed knowledge co-creation. This is reflected in the comment provided by Sanna Siri, research team leader of the Energy Efficiency and Systems Group: *"Basic information on what is happening in the electricity systems, what is right now the electricity production mode in any European country, that's nowadays available—that's the other link that I'm sending to you. So we need either the raw data, the input data for our models, or we need the electricity system data for calibrating our models so that we can see what happens in reality, and we try to reproduce that with our own models. So those are extremely useful".* Trusting collaborative networks of participants in research in the form of consortia, communities and crowds at the local, national, regional or global level invited to science production is a key normative element in science that contributes to extended knowledge co-creation. This idea was highlighted by Antti Ahvala, Associate Vice-President for Campus Development and research team leader of Group X: "*We have had workshops. Not only with all possible authorities and representants from the university, like the education side, but also from real estate, and then the actual schoolchildren and teachers, people from the management of the school. So that…the co-creation, co-designing processes are more inclusive*". Therefore, we synthesized an expansive institutional goal of open science in the digital era, which was observed in our study among research groups working on sustainability and climate change issues, as informed and extended knowledge co-creation.

4.2. Open data practice transforming research processes in sustainability

We found that open data practice is the major open sharing practice adopted by research teams when combating climate change and its impacts. Open data have radically transformed university research teams' processes of collecting, evaluating and circulating data and designing and performing scientific studies in the field of sustainability. First, we found that open data access and use (inbound) has become a cornerstone practice of the research process in sustainability. Second, we observed that data sharing (outbound) has enabled responsible, inclusive and sustainable research when combating climate change and its impacts and has increased the dissemination of raw data within academia and society. Third, we found that many of the university research teams reported efficiencies gained from

working with open data. When compiling open data (inbound), research teams have accelerated, reduced the cost, and increased the relevance of their research. By sharing their data (outbound), research teams have guaranteed the future accessibility and usability of their work. We found that data sharing is becoming a central inducing mechanism for knowledge transfer in the digital era. Finally, we identified the challenge of quality assurance demands for open data (inbound) and the challenge of opening up sensitive data sets (outbound), especially with qualitative data, when researching in the field of sustainability.

4.2.1 Open data as knowledge creation (inbound) and circulation (outbound) practice

We found that open data access and use by research teams has enhanced researchers' possibilities for theoretical modelling, performing analysis, testing solutions and enabling policy recommendations with better generalization and accuracy of dynamic phenomena. Researchers have developed complex and data-rich models for supporting climate change mitigation actions and policies. Ahti Salo, research team leader of the System Analysis Laboratory Group, explained how they *"have contributed to the International Panel on Climate Change reports (…) Tommi Ekholm, he developed the studies for the Finnish scenarios for 2100, supporting the climate change target, emissions targets for Finland in 2100 (…), and much of the data would come from public sources"*. We found that knowledge creation in sustainability has been led by compiling data from public, reliable and trusted datasets from international organizations (e.g., the United Nations), national governments (e.g., Finland's government) and public bodies (e.g., the Finnish Environment Institute). Harri Koivusalo, research team leader of the Water and Environmental Engineering Group, explained how their research is open-data driven, especially when working with natural water resources issues from the context of scarcity of resources*: "This research is very much based on open data […] data resources that are there are from United Nations […] data from the Finnish meteorological institute are open source, and […] when we are working with water resources, we are interested in the weather conditions, in the meteorology, with the climate sense projects, and so we very much rely on these open data".* Open data access and use have allowed researchers to participate in the research process of global sustainable solutions by obtaining access to distant resources of knowledge. Harri continued, *"They are working with developing countries, and their research very much relies on all sorts of open, large-scale data projects"*

We found that data sharing has become a rooted practice in the field of sustainability to increase the internal (academia) and external (society) accuracy, transparency, credibility, reliability and usability

of data. Marketta Kyttä, research team leader of the Spatial Planning and Transportation Engineering Group, described how this process is being undertaken by her research team: *"We are now going to, in the future, always publish our datasets in that (open) repository that we will select (…) we refer to those openly accessible datasets for, you know, if anybody wants to do further research or check our analysis"*. Data sharing is considered a movement from the paradigm of the dissemination of research results – a separate phase of the research process - to the circulation of knowledge – a new phase of the research process. We identified research teams' intrinsic and extrinsic motivators for knowledge circulation. First, we identified inclusiveness as intrinsic motivator. Researchers have opened up their datasets not only to advance science according to its ethos but also to democratize and allow worldwide research participation in science. Miina Rautiainen, research team leader of the Geoinformatics - Remote Sensing Group, explained, *"Some team members come from developing countries, and they have a very strong personal sense of duty".* Second, we identified career development as an extrinsic motivator. Researchers have shared their own datasets for other researchers to use and cite their studies, to increase the visibility of the research group, to promote their skills in collecting data and to find new public and private collaborations. Miina noted, "*It can be a motivation to get more citations of their own papers and to promote their own career"*.

4.2.2 Efficiencies in the research process from open data

We found that open data (inbound) practice has accelerated the research process in sustainability and reduced its cost. We also found that research has increased its relevance by supporting policy development processes. Scenario modelling and analysis has become quicker and is built on comprehensive, realistic, larger, and longer-term datasets. Sanna Syri, research team leader of the Energy Efficiency and Systems Group, explained the impact and value of this practice in her research team: "*It helps, tremendously, our work, all of this input data or comparison data freely and quickly available. So it speeds up our work; we can more easily develop our own scenarios of any systems that might be helpful, might be climate friendly, carbon-neutral"*. Researchers can gather, organize, interpret, and combine data from different private and public sources more efficiently and competitively. Minna Rautiainen, research team leader of the Geoinformatics - Remote Sensing Group, explained that *"open data has been a big thing (…) now we can get forty years' time series of satellite data for the whole planet for free".* Furthermore, we found that open data (outbound) practices are making the knowledge transfer mechanisms at universities evolve. Researchers are increasingly sharing their raw datasets to ensure the future accessibility and usability of their data for research and innovation purposes. One reason for this is that researchers may change their workplace,

and they want to have full access after relocation to the data they gathered or produced. Riikka Puurunnen, research team leader of the Catalysis Group, highlighted this mechanism*: "It's really an issue that what you did in the previous place stays there. And if you publish it openly, well, you always can access it yourself".* Additionally, researchers are opening up their data sets in sustainability research to provide societal, environmental, economic and cultural value. Kamyar Hasanzadeh, coordinator of the open data initiative in the Spatial Planning and Transportation Engineering Group, explained that everyone (citizens, researchers, firms or municipalities) can access their data for education, research and innovation purposes: *"Yes, the license we have used is quite flexible. There are no restrictions".*

4.2.3 Open data challenges in the research process

We identified the challenge of quality assurance demands for open data when compiling these data for research in sustainability. The accessibility of open data has not immediately brought trust. Researchers have been required to develop new skills, tools and support services to verify the robustness, applicability, and reliability of all data openly available on the web. As Harri Lipsanen, research team leader of the Nanoscience and Advanced Materials Group, expressed to us, *"You need an expert to really find out what is the truth, what is really relevant".* We also found that researchers have encountered challenges when sharing open data to enable sustainability research, such as the challenge of anonymizing data and maintaining the quality of data with regard to opening up sensitive data sets, especially for qualitative data. Making data available has made it difficult to promptly confer transparency. Researchers have been required to develop new skills and tailor-made protocols and infrastructures to share their research data fairly and ethically in line with GDPR regulations. Idil Gaziulusoy, research team leader of the NODUS Group, noted, "*Anyone who is doing qualitative research and who is doing research with humans knows that you need to consider the privacy of data, personal data; you need to consider whether that person is ok with being quoted openly or not".*

4.3. Transdisciplinary research practice transforming research processes in sustainability

We found that transdisciplinary research practice is a major open inviting practice adopted by research teams when combating climate change and its impacts. Transdisciplinary research practice has become a pioneering practice that drives the societal agenda in the field of sustainability. First, we found that transdisciplinary research practices by research teams have enlarged their research processes in terms of academic and societal engagement and collaboration by recognizing and

including new participants in very early research phases. Second, we found that many of the university research teams reported efficiencies gained from working with transdisciplinary research. Transdisciplinary research practices have promoted more targeted science outputs and strengthened knowledge recombination when combating climate change. Finally, we identified the challenges of the silo discipline mindset and current reward systems when adopting transdisciplinary research practice in the sustainability field.

4.3.1 Transdisciplinary research as knowledge recombination practice

We found that transdisciplinary research practice by research teams has boosted knowledge recombination – the agile creation and circulation of ideas, data, methods, and results – by authorizing new participants in several phases of the research process in science production. As Idil Gaziulusoy, transdisciplinary research team leader of NODUS Group, explained, *"We do see everyone as an expert, and we use the terms academic expert, non-academic expert, because everyone is an expert in something"*. We distinguished three dimensions of transdisciplinary research at universities. The first is academic transdisciplinarity, in which researchers from different research disciplines recombine their knowledge. Marjo Kauppinen, research team leader of the PREAGO Group, explained the value of a recent collaboration between the School of Science and the School of Arts, Design and Architecture: *"Having people from arts and design, it can make our research much more interesting, and it can create something special. So, they have a bit different research methods (…) they're now combining their research knowledge with our research knowledge".* The second dimension of transdisciplinarity, citizen science, focuses on researchers who engage with citizens to combine their knowledge. Researchers have not only gathered data from/through citizens; researchers have also authorized citizens in science production by engaging them in new research phases. Citizen science practices have evolved. A clarifying example of this new kind of citizen engagement was given by Marketa Kyttä, research team leader of the Spatial Planning and Transportation Engineering Group, who explained, *"It's a little bit problematic to co-analyse these datasets, but we have done that sometimes, for example, in this Helsinki City Masterplan project (...) there were some focus group events organized with the idea that groups of people would help us deepening the data".* The third dimension of transdisciplinarity, professional transdisciplinarity, involves researchers who combine knowledge with different professionals of public and private organizations (companies, municipalities, NGOs, states or international organizations) with the aim of having a better understanding of the state of the art and anticipating possible futures and alternatives when combating climate change. Antti Ahvala, Associate Vice-President for Campus Development and research team leader of Group X, provided an illustrative example of how to set up this practice among different

academics, professionals and students: *"So we have built a Lego model of the campus (…) So if you made changes in the Lego model, it shows changes in biodiversity, CO2 emissions, innovation capacity, and those kinds of things. But it's very important that the interface is user-friendly and open because anybody can play with Lego blocks. And they don't have to know anything about it (…) It's also good that it's an attraction for people to gather there, and we can play with politicians and city officials".* We found that these three dimensions were combined according to the nature of the research topic and the expertise required of the participants. Transdisciplinary research practice has become a holistic open science practice that does not use only one open science practice but rather combines several, including action research, co-creation platforms, crowdsource practices, interdisciplinary research practice, open physical labs and participatory design. Pirjo Kääriäinen, research team leader of the CHEMARTS Group, provided an open-minded perspective on this: *"You have these open labs […] BioGarage was just opened last week in a design factory now by four of us for some genetic engineering stuff. So of course that's one way to try to take more and more people to get them involved this bio art; there are different kinds of labs and hubs and so on where anybody basically is supposed to be able to come and work, hack things and so on".* In summary, knowledge recombination by transdisciplinary research practice allows multiple science disciplines to explore new knowledge avenues in the field of sustainability.

4.3.2 Efficiencies in the research process from transdisciplinary research practice

We found that university research teams working with transdisciplinary research practices have gained efficiency. Transdisciplinary research practices have promoted more targeted science outputs when combating climate change. Researchers have obtained ideas, data, methods and results that better take into account societal needs by recognizing, including and integrating scientific, professional, and citizen knowledge from the conceptualization phase of research. Juanjo Galán, research team leader of the AaltoLand Group, highlighted these efficiencies: *"In climate change, we are talking about how communities can get engaged in climate change adaptation; basically, we need to know what the needs of those communities are and how they can participate. We don't want to give them a ready product; they are part of the process".* We further found that the constant interaction between researchers and participants through transdisciplinary research practices has strengthened knowledge recombination. As Mark Hughes, research team leader of the Wood Material Technology Group, explained, *"I suppose that's the most structured form of co-creation that I've experienced. Yeah, that's been very beneficial, because then you've got clear outputs from the time you spent together"*.

4.3.3 Transdisciplinary research practice challenges

We found that the silo discipline mindset has inhibited transdisciplinary research practices. Yrjö Neuvo, Research Director in Energy Conversion and Aalto Energy Platform, shared this concern and discussed how new singular transdisciplinary research platforms have tried to overcome it by promoting cross-fertilization among participants in research: "*Silo thinking is a really big risk. And there are so many different truths, so one really has to have breadth and curiosity. I think that in the platform (…), we have broad understanding, we can organize innovative events".* He continued, *"Transdisciplinary all the time—that has been kind of my guiding principle over the years".* We also found that traditional research incentives – reward systems – have inhibited the adoption of transdisciplinary research practices by research teams. Pirjo Kääriäinen, research team leader of the CHEMARTS group, provided an illustrative example of this concern: *"If we want to do something, we need to have two articles, for example, one that will be for the scientific and technical community and the other for the design community. It's quite interesting and it's one of the problems…it's been recognized and we really also try to tackle".*

4.4. A new academic entrepreneurial ethos transforming research and innovation in sustainability

In addition to changes in the open science practices and norms among researchers in the field of sustainability and climate change, our study reveals how researchers are increasingly becoming entrepreneurial in their work. Of the 23 team leaders we interviewed, 15 had gone beyond existing ways of doing research by being innovative and entrepreneurial in setting up knowledge co-creation activities and being explorative in knowledge value creation, circulation, and recombination work. In their efforts, we found that the boundaries between research and innovation are increasingly diffuse. It is difficult to separate where research ends and where innovation begins, as also noted by our informants in the earlier sections. We found that research and innovation intertwine and are happening at the same time, especially among university research teams who attest to expansive openness in sustainability research. It is this expansive openness that causes open science and open innovation to take place at the same time. We next present a synthesis of our findings regarding what we consider a new type of academic entrepreneurial ethos that encompasses three distinguishing characteristics of moral nature and guiding beliefs that drive research and innovation in sustainability at universities: (1) the adoption of expansive norms of open science; (2) a mindset of radical

creativity, a sense of initiative, and passion for exploring new innovative solutions; and (3) the promotion of responsibility and inclusiveness as key values.

Through our in-depth analysis of 23 research groups, we found that the development of global actions, solutions and technologies for combating climate change through open science and innovation practices was led by a new type of academic entrepreneur. All of the research groups embraced the expansive norms of open science in their development of global actions, solutions, and technologies for combating climate change. Riikka Puurunnen, research team leader of the Catalysis Group, provided a good example of this expansive norm of open science as part of her academic entrepreneurship: *"I'm openly discussing things, for example, on Twitter: work-related things, research-related things, funding-related things, problematic terminology, all kinds of things*". In our studied research teams, we found individuals who embraced a new kind of academic entrepreneurial mindset built on radical creativity, a sense of initiative and a passion for exploring new, innovative solutions. Yrjö Neuvo, Research Director in Energy Conversion and Aalto Energy Platform, explained this mindset: *"First of all, it means curiosity. Desire to learn and discuss. Also, it's not being too formal, too strict. You have to accept different ways of thinking and different attitudes and policies … mental flexibility is a pretty good term for that"*. Finally, we found that the research leaders and researchers working on climate change in the teams we studied promoted responsibility and inclusiveness as key values as part of their academic entrepreneurship. A comment by Marko Nieminen, research team leader of the Digital Opportunities Group, captures the essence of these values: *"If we are developing some new services that we hope are somehow having some societal impact, we need to have the possibility to include the citizens, people who are being influenced by those, let's say, future services that we are studying, somehow, in the early stages".* He continued, *"It cannot be done only by the developers, only by the designers, only by the researchers; you must include the viewpoints arising from the context that you aim to affect somehow or understand in your research or affect through your designs".*

This new academic entrepreneurial ethos is changing the role of researchers who are researching and developing innovative solutions for combating climate change in the field of sustainability. Researchers have developed new actions, solutions and technologies beyond the traditional conventions for organizing and managing research and innovation at universities. A statement from Mark Hughes, research team leader of the Wood Material Technology Group, reflects this idea: *"I think the boundary between research and innovation is a little bit more blurred, at least in my mind now. I'm not quite sure what we do, whether we are doing innovation or whether we're doing*

research half the time; it's a little bit of both, I think". The role of researchers is currently evolving from lab-desk science management towards platform-community science management, from "pure scientist" (Saarela, 2019) to academic entrepreneurs. Researchers are simultaneously learning, researching, and innovating together with a wide set of participants to achieve a sustainable world. Their activities exceed what is currently promoted, recognized, and rewarded through the existing research, innovation, and knowledge transfer mechanisms at universities. Researchers are becoming active explorers of knowledge, solutions, and processes to solve societal challenges. We assert that this new academic entrepreneurial ethos is expanding the role of researchers in the digital era and, with it, the traditional process of knowledge value creation and transfer at universities.

5. Discussion

Our study makes a major theoretical contribution by advancing the understanding of the social structure of the open science institution in the digital era.

First, we update the responsible, social and sustainable goal–an expansive institutional goal–of open science. The "institutional goal" of open science as synthesized by Merton is the "extension of certificated knowledge" (Merton, 1973, pg. 270). Based on our findings, we suggest that the goal of open science in the digital era has evolved to encompass *the expansion of informed and extended knowledge co-creation*. Recognizing this updated institutional goal is key for understanding, defining, and managing the research process in the digital era.

Second, we identify a new set of expansive norms underpinned by the transparency and accessibility to science outputs and authorization and participation in science production. We find that the "institutional imperatives" (Merton, 1973, pg. 270) of open science in the digital era, the new set of expansive norms of open science, build on Mertonian norms of communalism, universalism, disinterestedness, and organized scepticism (CUDOS) but expand the ethos in science in terms of cooperation between collaborative networks of participants in research: researchers, universities, research institutes, companies, NGOs, states, municipalities, citizens, and international organizations.

Third, we show how open data (inbound and outbound) and transdisciplinary research practices, "technical methods" (Merton, 1942 in Merton, 1973, pg. 270), the new expansive open science practices in the digital era, are radically transforming the traditional knowledge creation process – the research process. We propose that the new research process in sustainability research with these new open science practices seeks out informed and extended knowledge co-creation through knowledge

creation, circulation and recombination by including collaborative networks of participants in research from the very early conceptualization and design to the following research stages.

As such, our findings contribute to the academic foundations of the philosophy, sociology and economics of science in the evolving digital era. We infer an expansive normative structure of open science among researchers working on sustainability that is key for designing and fostering efficient science public policies in the evolving digital era. This new expansive normative structure of open science enables a "change of paradigm" (Kuhn, 1970) with regards to the previous modern or open science institution era. The new practices, norms, and institutional goal of open science trigger a new paradigm for co-creating scientific knowledge in the digital era. By informing and extending the research process to more collaborative networks of participants, including scientific, professional and amateur users of scientific knowledge, science disciplines–theories–are evolving. Researchers are recombining ideas, gathering new data, adapting new methods and using new results from other disciplines and other participants in the sharing and production of science outputs for sustainable development. Our conceptual model of the expansive normative structure helps researchers identify and articulate what we call a second open paradigm in open science's social institution, which occurs in the ongoing evolving digital era in our society today.

Finally, our study makes a contribution by identifying a new entrepreneurial ethos with distinct norms, mindset and values in academia related to the simultaneous efforts to research and innovate solutions to advance sustainability and combat climate change. This new academic entrepreneurial ethos advances the role of researchers at universities (Perkmann et al., 2013) in the evolving digital era from lab-desk science management towards platform-community science management, from pure scientists (Saarela, 2019) to academic entrepreneurs.

The expansive normative structure of open science in the digital era and the new academic entrepreneurial ethos are expanding the second and third missions of universities. First, the new normative structure is transforming universities' traditional organizational structure of science-basic research, applied research and experimental development (OCDE, 2015). Open science's new practices, norms and goal are expanding research fields' openness and, with it, the standard boundaries between research disciplines. We find initial evidence of how the overall openness of a research field varies in relation to the involvement of participants in the research field and the maturity of the research field. Expansive openness in science goes beyond the traditional borders of conventions of organising science disciplines and is reflected and extended in a multitude of arenas of knowledge development, including basic research, applied research, humanities, experimental development, design and art. Second, the new academic entrepreneurial ethos is evolving the

traditional rewards systems for scientists and knowledge transfer mechanisms. At the centre of this new ethos is our study's observation that openness in science can become an impactful incentive and mechanism for the creation of actions, solutions and technologies that simultaneously address cultural, economic, environmental, societal, and technological value. Open science practices achieve knowledge and technology transfer from the first steps of the research process by including participants in the informed and extended knowledge co-creation process.

The new academic entrepreneurial ethos can be considered itself an institutional model for universities working on sustainable development in the digital era. Past research on academic entrepreneurship has dominantly focused on researchers' commercialization activities (i.e., Braunerhjelm, 2007; Walsh & Huang, 2014) as well as their teaching and mentoring in entrepreneurship (Siegel & Wright, 2015), although progress in widening academic entrepreneurship's definition has been promoted (Abreu & Grinevich, 2013). Our findings expose how academic entrepreneurship has evolved to encompass professionals who act as enablers of institutional change (Suddaby and Viale, 2011) in society and in the public and private sectors. As academic entrepreneurs, professionals in the university, i.e., researchers and university managers, are increasingly acting as institutional change agents by developing, testing, and adopting new practices, norms, and cultural-cognitive models (Scott, 2008). Such institutional change activities include spearheading and promoting new standards, new practices and cognitive norms of research within their social structures, including the university and the scientific fields in which they work in. The key values embraced by academic entrepreneurs–the expansive norms of open science, the mindset of radical creativity, the sense of initiative and passion for exploring new innovative solutions, and the promotion of responsibility and inclusiveness–can be viewed as the university model's core parts in the digital era.

Based on our findings, we propose an expansive model (see Figure 2) of university research and innovation led by entrepreneurial academics to guide the renewal of university governance in the digital era. This model can drive institutional change at universities. The new open science practices are expanding not only the ethos in science but also in innovation at universities. These new practices and the new entrepreneurial ethos by academics are transforming the established knowledge value creation and transfer process – the innovation process - in the digital era. We find that researchers have adopted open science and innovation practices with the aim of promoting informed and extended knowledge value co-creation, including knowledge value creation, circulation and recombination, among multiple participants in research (e.g., researchers, universities, research institutes, companies,

NGOs, states, municipalities, citizens, and international organizations) and multiple types of value (e.g., cultural, ecological, economic, technological, societal, or a hybrid combination of the five). We call this process in which entrepreneurial academics are engaged "open exploration", which encompasses informed and extended knowledge value co-creation through open science and innovation practices. Open exploration is a new holistic research and innovation process at universities for advancing knowledge and developing actions, solutions, and technologies to achieve sustainable development.

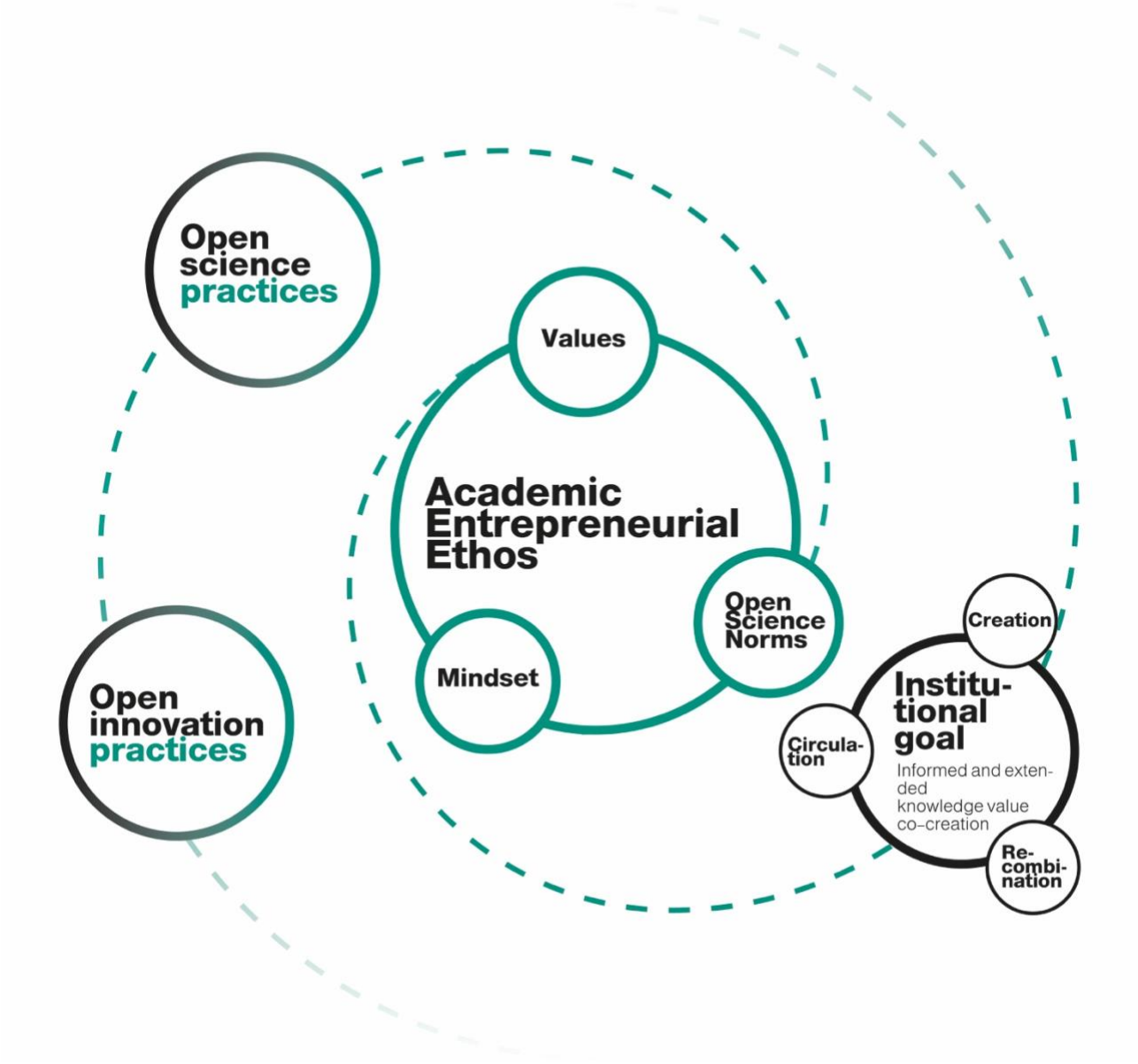

Figure 2. Open exploration: an expansive model of university research and innovation in the digital era.

Our findings have been inferred from an empirical study of research teams working within the sustainability field at one university. Like any university, this specific university is part of a society that promotes and encourages the philosophical principle of openness to guide and support the progress of society through reason and knowledge. Future research should therefore explore how the expansive normative elements–practices, norms, and institutional goal–of open science in the digital era operate in other research teams, in other research areas, in other universities, and in different national and international contexts. This will aid the measurement of the impact and efficacy of the normative elements of open science in the digital era. Furthermore, future research could also focus on how particular digital technologies and tools and/or open physical and digital infrastructures specifically expand these normative elements in specific research fields.

Our study provides several policy implications for university leaders and science and innovation policy makers. First, our study provides a solid understanding of the goal, norms, and practices of open science and their responsible, societal and sustainable value as well as the efficiencies gained. These insights are central when designing effective university science and innovation public policies that promote the achievement of the Sustainable Development Goals established by the United Nations. Second, the proposed new open exploration model for research and innovation requires that universities rethink their second mission–research–and their third mission–knowledge and technology transfer–in the evolving digital era. Universities, as the main public infrastructure for open science and innovation, need to update the way that research and innovation are administered, organized and managed. Universities, therefore, need to renew existing governance models and mechanisms to incorporate the expansive model for research and innovation in the digital era. Such governance mechanisms include research agendas, science reward systems, talent management systems, knowledge transfer mechanisms, and socioeconomic interactions with the ecosystem and public engagement. In essence, our findings provide novel insights and important directions on how to advance an open exploration policy for holistic and public scientific knowledge co-creation and transfer at universities to address societal grand challenges, promote well-being for all, and boost a sustainable economy, society, and environment–in sum, for a sustainable world.

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Appendix 1

Protocol Questions

1. What does it mean to be open?

2. Is your research team sharing their science outputs with other researchers, research institutes, companies, municipalities, citizens or international organizations?

3. Is your research team co-creating science outputs with other researchers, research institutes, companies, municipalities, citizens or international organizations?

4. Are open sharing practices affecting the research process of your team?

5. Are open inviting practices affecting the research process of your team?

6. Are open science practices changing the innovation practices of your team?

7. What is the role of researchers in the open science phenomenon?

8. What are the skills that your research team needs to conduct open science research?

9. What prevents open science and open innovation practices from developing solutions for combating climate change and its impacts?

10. How do open science practices contribute to society? economics? science and technology?