European Commission

Study on factors impeding the productivity of research and the prospects for open science policies to improve the ability of the research and innovation system

Research and Innovation

Study on factors impeding the productivity of research and the prospects for open science policies to improve the ability of the research and innovation system to transform financial investments in research into valuable outputs such as breakthrough innovations

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EUROPEAN COMMISSION

Study on factors impeding the productivity of research and the prospects for open science policies to improve the ability of the research and innovation system

Final report

European Future Innovation System Centre

2022 Directorate-General for Research and Innovation

Contents

OVERVIEW

Objective

This report aims to review evidence on three related lines of enquiry at the core of the current debates on research policy and practice: (i) **factors that can hinder the productivity of research**; (ii) **prospects for open science practices to improve research productivity**; and (iii) **the ability of research and innovation systems to transform financial investments in research into valuable outputs and societal outcomes**. We combine evidence on these topics to devise areas of action and policy guidelines to transform research and innovation systems to make them more productive and impactful. The following questions guided our research.

- How can we define research productivity?
- What are the evidence for and perceptions of a decline in research productivity across sectors and disciplines?
- What are considered the main factors that can hinder or improve research productivity?
- Can higher research productivity lead to a greater societal impact?
- What is the role of open science in research productivity?

To answer the above questions, we combined three different research designs, namely:

- a systematic review of the literature (over 200 papers were selected) on the definition of research productivity, its potential decline, and hindering factors and remedies;
- an exploratory survey of 52 experts designed based on insights from the literature review, to further analyse research productivity and to review in more depth the role of open science;
- a workshop with eight experts to discuss in an articulated way the results of the literature review and of the exploratory survey, to identify policy options.

Main insights

Definition of research productivity

We identified three main frameworks to define research productivity and summarised them as follows.

1. **Scientometric framework.** Research productivity is studied as the ratio of research inputs (e.g. funding and human capital) to knowledge codified in bibliographical outputs (publications and patents).
2. **Innovation framework.** Research productivity is studied as the ratio of research inputs (e.g. funding and human capital) to innovation outputs (e.g. technologies, patents and ideas).
3. **Societal impact framework.** Research productivity is studied as the relationship between research inputs, how they are organised and prioritised, and their effects on society.

Because of the importance of the innovation framework (framework 2) to policies currently being developed by the European Commission, it was the focus of the rest of the review and analysis.

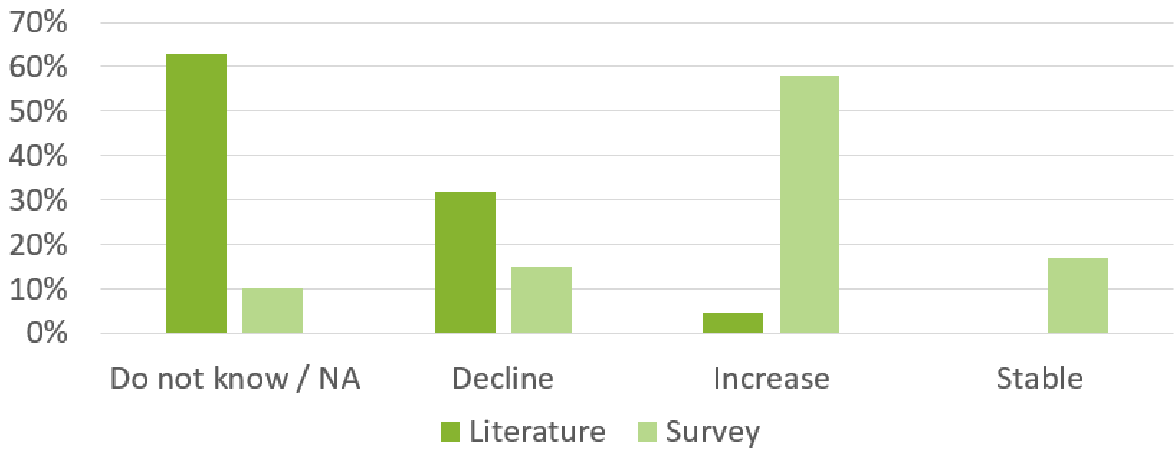
Research productivity decline: the literature and respondents' perceptions

Approximately 32 % of the reviewed studies mention a decline in research productivity. These are studies that directly analyse changes in research productivity, or studies that refer to earlier research. More than 60 % of the sampled literature that discusses research productivity (in framework 2) does not mention a decline.

Only approximately 15 % of respondents in our exploratory survey said that research productivity had declined in the past 10 years.

Over half of the respondents (58 %) claimed that research productivity had increased, while very few of the reviewed studies mention an increase.

Figure 1. Percentage of papers in the literature review and survey respondents reporting changes in research productivity (%)



Hindering factors: the literature and respondents' perceptions

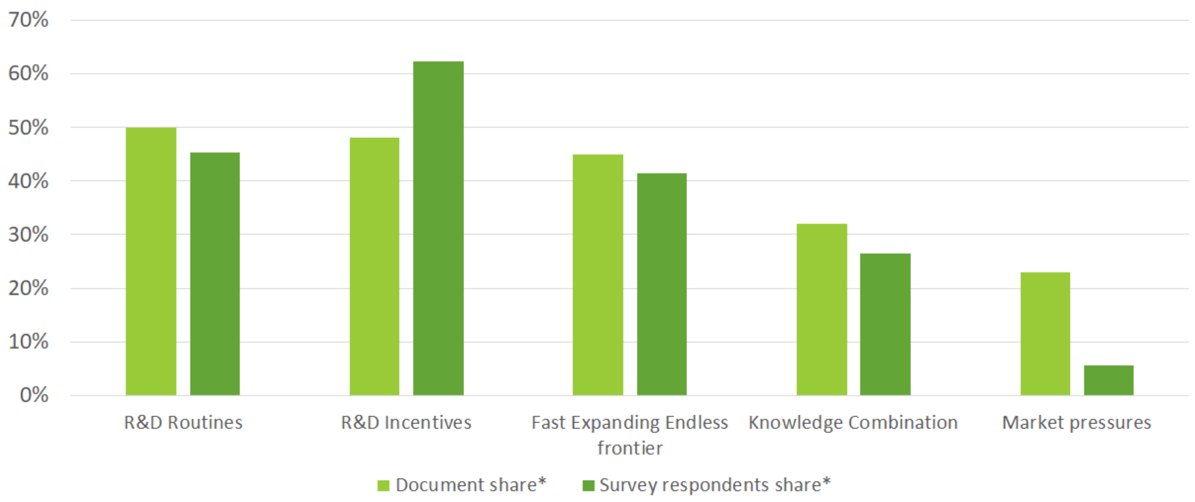
The literature and the survey respondents identify many factors that hinder research productivity. Some of these are related. We grouped them into the following main categories (each composed of several subcategories).

- **Research and development (R & D) routines.** Innovation processes and routines have changed substantially over time and vary across sectors. As new technologies and new organisations emerge, R & D processes need to adapt (see, for example, studies in the area of artificial intelligence (Cockburn et al., 2019) and the pharmaceutical industry (Henderson and Cockburn, 1996; Owens et al., 2014; Cobb et al., 2019).

- **Market pressure.** Incentives are often driven by profits and not the need to expand knowledge to improve social welfare (Wallace and Rafols, 2015; Sarewitz 2016; Gold, 2021).
- **R & D incentives.** Aside from market pressures, several policies shape innovation incentives in ways that are not aligned with breaking new boundaries (Brown et al., 2017; Fortunato et al., 2018; Koutroumpis et al., 2020).
- **Fast-expanding endless frontier.** New knowledge is essential for innovations, but, as the frontier of new knowledge needed for innovations expands, new knowledge is more difficult to achieve and more investments and talents are needed (Bush, 1945; Kortum, 1997; Jones, 2009; Bloom et al., 2020; Chu and Evans, 2021).
- **Knowledge combination.** Although innovation is a process of knowledge recombination, and radical innovations tend to emerge from the combination of vastly different knowledge components, such combinations are risky and are increasingly difficult to produce (Ziman, 2000; Fleming and Sorensen, 2004; Arthur, 2009).

Most of the sampled literature discusses the hindering factors of **R & D incentives** dictated by regulations and evaluation systems in science, and of specific **R & D routines** (Brown et al., 2017; Gold, 2021) Many studies also focus on the **fast-expanding knowledge frontier** (Pammolli et al., 2011), the increasing costs of advancing knowledge and the divergent competencies required to advance knowledge for innovations.
The relative frequency of the hindering factors mentioned by the survey respondents is similar to that found in the the sampled studies, with one relevant exception: there is little mention of market pressures. Moreover, respondents highlight the issues of evaluation pressure (in the R & D incentives category) and R & D management (in the R & D routines category) more frequently than the sampled studies.

Figure 2. Percentage of papers in the literature review and survey respondents reporting hindering factors (%)



Remedies

The literature and survey respondents identify various remedies to improve research productivity. We grouped them into the following main categories (each composed of several subcategories).

- **Improving R & D routines.** Specific aspects of R & D processes can be improved to combat hindering factors in various ways. These include using new technologies and methods (Pammolli et al., 2020), providing open access and improving reproducibility (Gassmann and Reepmeyer, 2005; Bowen and Casadevall, 2015), and improving collaboration (Baba et al., 2009; Belderbos et al., 2015).
- **Improving governance.** Several hindering factors could be addressed with better policies, such as intellectual property rights (Brown et al., 2017; Habib et al., 2019), better regulations and several policy instruments to steer incentives (Garnier, 2008; Pammolli et al., 2011; Bowen and Casadevall, 2015; Pammolli et al., 2020).
- **Improving management and organisation.** Beyond R & D processes, improvements could be made in the management and organisation of research intensive organisations and their research labs (Paul et al., 2010; Cummings and Knott, 2018).
- **Setting strategies based on R & D priorities.** To combat hindering factors that push for increased specialisation and siloed knowledge, there are several ways to modify the incentives of organisations and scientists to reduce (or increase) specialisation (Cuatrecasas, 2006); reduce the focus on bibliometric evaluations (Bhattacharya and Packalen 2020); and increase the focus on diversification (Kissin, 2010), paradigm shifts (van der Greef and McBurney, 2005; Jones, 2009) and the societal impacts of R & D (Hoos et al., 2015).
- **Increasing R & D funding.** Remedies in this category increase private or public funding to counteract the diminishing returns of knowledge production (Henderson and Cockburn, 1996; Raymond et al., 2015; Bloom et al., 2020).
- **Improving access to human capital.** Different strategies can be used to improve access to or the retention of skills and talents in R & D (Habib et al., 2019; Goel and Göktepe-Hultén, 2021).

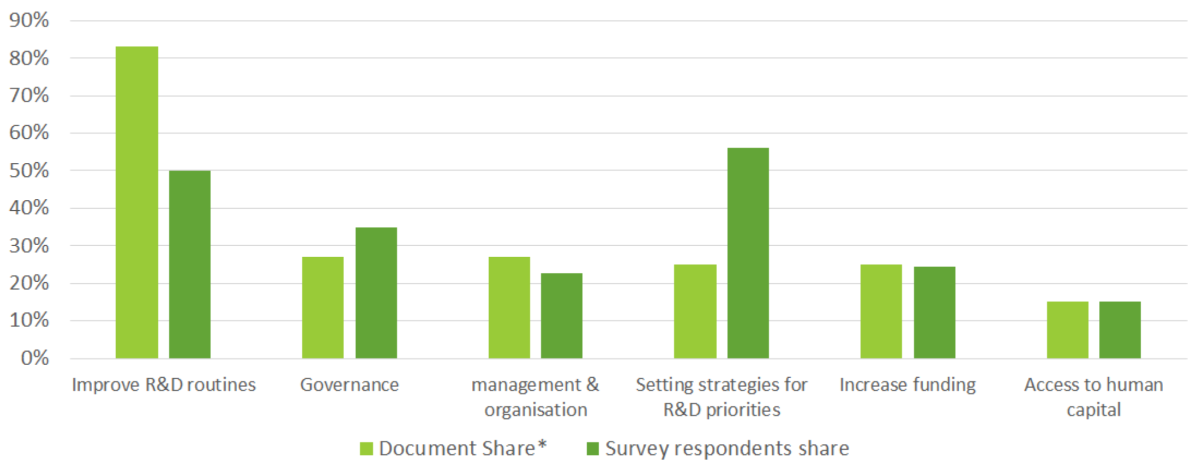
The most relevant category to improving research productivity discussed in the sampled literature is **improving R & D routines**). Improving R & D routines is also one of the two most frequent categories of factors that can improve research productivity indicated by the survey respondents. Where the literature and the survey respondents differ is in specific actions. Although both mention improvements in collaboration and R & D management, increasing interdisciplinarity and using open access practices, the literature also focuses on new methods, technologies and open science.

Survey respondents also strongly recommended remedies related to **setting strategies for R & D priorities** (more frequently than among the selected studies). Specifically, researchers considered transforming research evaluation systems the most important to increase research productivity.

Other more specific remedies indicated by survey respondents were firm management, increased public funding and better governance.

Respondents to our survey did not identify remedies related to market strategies, incremental innovation and specialisation. These issues may be more relevant to entrepreneurs and managers.

Figure 3. Percentage of papers in the literature review and survey respondents reporting remedies (%)



Open science and societal impact of research

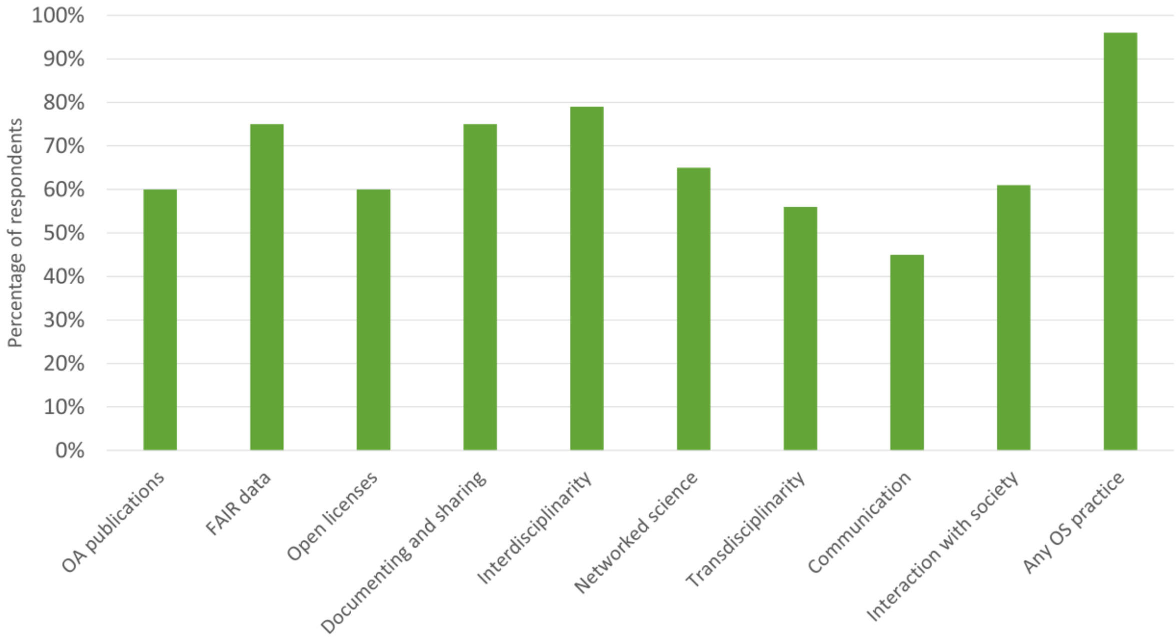
Survey respondents were very positive about the contribution of open science practices to research productivity. Most of them (96 %) identified at least one open science practice as potentially relevant to increasing research productivity. Interdisciplinarity was identified as relevant by the most respondents (79 %), followed by operationalising findability, accessibility, interoperability and reusability (FAIR) data principles (75 %) and documenting and sharing workflows and methods openly (75 %) (Figure 4).

The majority of respondents (63 %) also believed that open science practices do not hinder research productivity. The main open science practices that respondents thought could have a negative impact were open licences (12 %), operationalising FAIR data principles (12 %) and interdisciplinarity (12 %).

The majority of survey respondents (83 %) considered that open science could help to address the two hindering factors that they had indicated in their earlier responses. They considered that open science practices contribute to solving issues related to the fast-expanding endless frontier, to the complexity of knowledge combination, and to R & D incentives and R & D routines.

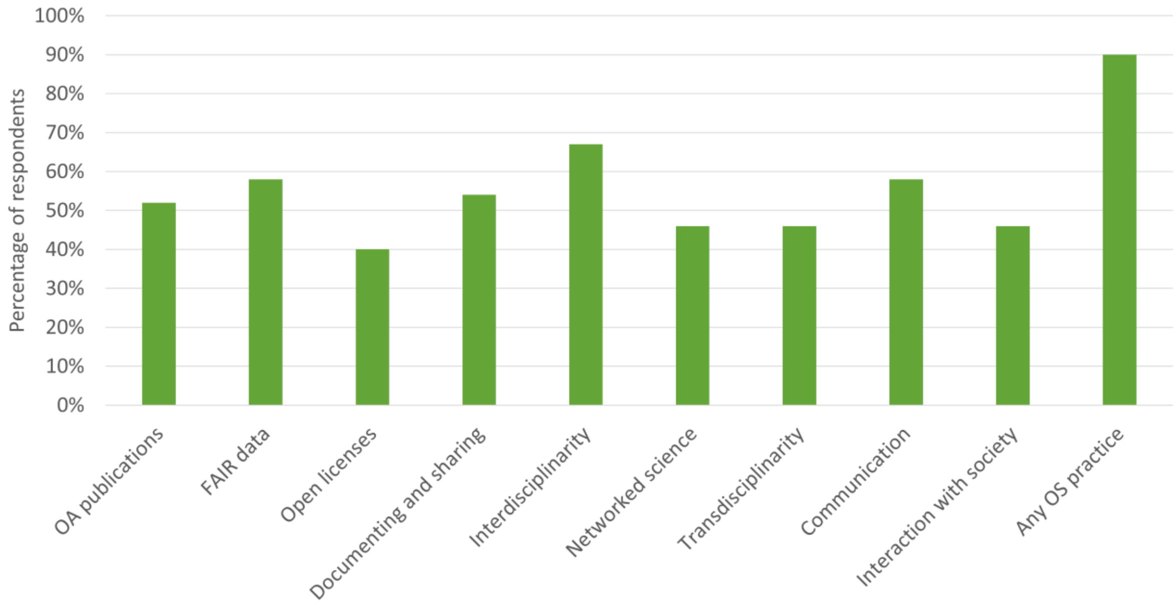
Some 63 % of survey respondents also provided examples of the role of open science in improving research productivity in terms of improving research efficiency (e.g. open data reduces the costs of data collection), increasing the quality of research (e.g. replication is facilitated), problem solving (e.g. research questions are better informed by societal needs), creating awareness (e.g. scientists learn new methods or identify new collaborators, or the public's perception of science is improved) and improving communication (e.g. scientific results are communicated faster).

Figure 4. Contribution of open science to research productivity



Some 90 % of survey respondents also considered that at least one open science practice could contribute to a large or very large extent to increasing the societal impact of research.

Figure 5. Contribution of open science practices to the societal impact of research



Policy insights

Although most of the existing literature and sampled experts do not identify the decline in research productivity as a general trend across sectors, and although the extent of evidence for and perceptions of a decline in research productivity depend on how it is defined, both the literature and the experts identify research productivity as a central problem, particularly with regard to the need to improve its measurement in relation to the areas of innovation and their diverse impacts on societies. The impact of the organisation, funding and governance of science on research productivity needs to be better understood.

Combining evidence from the literature, the survey and a discussion with several experts during a workshop, we put forward the following five complementary policy recommendations:

1. **Efficiency: increasing R & D funding may be necessary, but it is not sufficient**

   Although there is a need to increase funding to expand the knowledge frontier and maintain the current level of research productivity, the literature and experts focus on other factors hindering productivity: existing R & D incentives that promote incremental, low-risk and short-term research, with no clear impact on societal well-being (owing to current regulations, market and non-market evaluations of research, and the extreme specialisation of research), and inefficient R & D routines and processes (owing to regulations and the slow uptake of innovative tools and methods).

   For R & D to be more productive in generating innovations that lead to socioeconomic benefits, there is a need to:

- facilitate the development of human capital and access to talents that break existing socioeconomic barriers, as this is the creative input that transforms funding into knowledge and innovations, and is a key component of achieving impact;
- better plan and design research funding, including processes for defining priorities, interacting with research users to strengthen the links between research and society, and promoting high-risk R & D projects;
- promote the diffusion of organisational and technical innovations that improve the efficiency of R & D routines;
- promote and facilitate collaborations between researchers, and across organisations, disciplines and sectors, funding the time needed for those collaborations;
- explore and understand the effects of different incentives and policies on researchers' motivation to look beyond and expand the knowledge frontier.

2. Changes in research funding priorities: balancing relevance to societal challenges, diversity and failures

Most of the research in the world is done on issues unrelated to major societal challenges (e.g. the sustainable development goals). Changes in the design of research funding policies in response to challenges (e.g. climate change, deep social inequalities, violent conflicts and the health problems of the most marginalised) may help to generate innovations/ideas that are more relevant to society and increase research productivity, beyond research efficiency. The focus on grand challenges should be complementary to an expansion, rather than a reduction, in the space for researchers to explore ideas with a low probability of success, but with potentially high impacts and novelty. This includes undertaking inter- and transdisciplinary research and pursuing radically different avenues for research (that may produce only a few successful innovations).

3. Changes in research evaluation practices and in the measurement of research productivity: combining efficiency and societal impact

Neither of the previous recommendations is likely to work under the current incentive system designed by market and non-market regulations and evaluation practices. Evaluations based exclusively on bibliometric assessments and market pressures that privilege high returns on innovation investments provide a strong incentive to focus on incremental changes rather than more radical breakthroughs. There is a need to understand how funding and assessments should be designed and organised with a focus on increasing research productivity that also has a larger social impact. How to revise evaluation systems is beyond the scope of this report, but we outline a number of options that could be explored in further research.

- The evaluation of research should fit the purpose of the evaluators or the policy programmes that support the research.
- We need learning systems for both the policy programme and the researchers to build collective capacity and reflect on the evaluation of both the design and the execution of R & D projects' funding.
- Evaluations based on bibliometrics are a useful complement. However, guidelines and recommendations that explain shared good practices, such as the Leiden Manifesto and the Declaration on Research Assessment, should be used.

4. Open science policies: open science practices may increase research productivity, but they need adequate support

Open science may improve research productivity at a systemic level owing to its effects on research efficiency (avoiding duplication, and increasing the use of knowledge stocks and collective intelligence); research reliability (owing to increased transparency and reproducibility); and research responsiveness to social needs (diversity and plurality in scientific participation could facilitate the identification of problems, and increased trust and visibility may promote policy dialogue).

As the social benefits of open science are greater than the individual benefits, and the individual (administrative) costs may be high, public policy can address obstacles to open science adoption. The following are a few suggestions:

- evaluation schemes should incorporate a wider set of outputs, including open data, and practices such as creating networks, engaging with society, and communicating and translating research outputs for a wider audience;
- the investment required to conduct transdisciplinary and interdisciplinary research collaborations should be considered in the design and evaluation of funding;
- regulations should provide more incentives to collaborate and share data and information;
- scientific communication practices should be regulated to guarantee maximum communication and minimum cost to the producers and consumers of knowledge;
- technical, institutional and infrastructural support and training for researchers on open science practices is needed;
- Institutional support is required to develop and implement harmonised open data policies.

Open science may also lead to less variety, if the availability of data means that less effort is made to build different datasets from different sources. The focus should then be placed on maintaining variety where open science practices may result in a reduction in exploration.

5. Systemic changes in the value chain of research and development practices

For the above policies to be successful, it is necessary to foster coordination between funders, researchers and research users to change research practices, priorities and evaluation. Prevailing funding, research and evaluation practices may not support a research culture directed at creating social value. Rather, they prioritise the production of knowledge that increases the efficiency of organisations or individual researchers. Understanding research productivity from the innovation and social impact perspectives requires the revision of these models. This includes documenting and creating new funding mechanisms and supporting academic practices that promote high-risk and 'unproductive' research; publishing and giving a high score in evaluations to publications that report failed experiments, and not only successful ones; having open deliberations about what areas should be prioritised; and including the research beneficiaries in these decisions.

At governance level, there is a need to implement strong collaboration mechanisms between research institutions and non-academic stakeholders (research users).

As part of this process, there is a need to move away from a definition of research productivity that solely considers the ratio of research inputs to innovative outputs, towards a definition that includes the societal impacts of research as outcomes. This will require major efforts to identify and develop data and indicators to capture long-term outcomes, recognising the value of failures and attributing these outcomes to research outputs. Adopting a definition of productivity that considers the societal impact of research at policy level will also require infrastructures and management strategies to be built that adequately support interdisciplinarity, transdisciplinarity, high-risk research and open science, key issues that were identified in this study and that merit further research.

INTRODUCTION

In this report we seek to better understand what is meant by research productivity (RP), and identify factors influencing RP and the potential for open science (OS) to improve the ability of the research and innovation (R & I) system to generate valuable results that have an impact on society.

To do so, we aimed to address the following questions.

1. How can we define RP? What theoretical and empirical frameworks do researchers use to measure and investigate RP? More specifically, what are the input and output variables used to measure it?

   We defined RP as the ratio of research inputs (e.g. funding and human capital) to innovation outputs (e.g. technologies, patents and ideas). Improving RP requires an improvement in the efficiency of the research system or funding used to generate/develop innovations, which in some cases may also lead to socioeconomic benefits. We are particularly interested in the impact of research on tangible innovative outputs other than publications.

   Addressing this question was crucial to provide a common starting point for and to define the boundaries of our study. It was especially useful in defining policy options that do not depend on different definitions of RP. However, it is also important to acknowledge that findings from this study and suggested policies are conditional to the specific definition of RP that we use in the study.

2. What are the evidence for and perceptions of a decline in RP across sectors and disciplines?

   We found that there is no consensus, and there are differences between studies, mainly in the area of life sciences (pharma and biotech), and the perceptions of experts and social scientists. Overall, there is no shared view that RP has declined.

Addressing this question, with the working definition of productivity used in this study, was crucial to frame findings in relation to whether scholars and experts consider that there is a more general and long-term need to improve RP or whether they see the issue as a contingent problem of our times.

3. What are considered the main factors that can hinder or improve RP?

   There are many factors that may hinder RP, as defined above, including incentives to focus on short-term rewards and career progression, outdated research and development (R & D) routines, barriers to combining knowledge, and slow expansion of the knowledge frontier. To address these factors, a large number of potential remedies have been proposed. These include improving R & D routines, changing priorities, improving the governance of R & D investment and simply increasing funding.

   It was important to compare evidence from the literature, focused on specific sectors, with the experience of researchers and experts. The views do not always coincide.

4. What is the impact of RP?

   Although the definition of RP used in this report relates to the efficiency of producing more innovative outputs, the crucial issue is the extent to which such innovative outputs affect economies and societies. Otherwise, as indicated in the discussion with experts during a workshop, there is a risk of incentivising incremental research, at the cost of more high-risk and radical research that has a higher probability of failure.

5. What is the role of OS in RP?

   OS practices may contribute to addressing a number of the factors hindering RP and contribute to potential remedies. As OS practices were not discussed in the literature that we reviewed, we asked survey and workshop participants this question. Although there were different views, we found that OS may have a role in increasing RP and addressing hindering factors. The two main contributions of OS are to (i) improving collaboration among scientists, especially to facilitate interdisciplinarity; and (ii) open access and sharing of research outputs, especially through operationalising findable, accessible, interoperable and reusable (FAIR) data principles and documenting and sharing workflows and methods. OS also seems to be important in improving the societal impact of an increase in RP.

To address the above questions we combined three different research designs.

- A systematic review of the literature on RP, which contributed to:
  - a) exploring the frameworks that are used to analyse RP and determining a definition of RP to be used for the rest of the analysis (RQ1);
  - b) analysing evidence and perceptions of a decline in RP (RQ2);
  - c) listing all potential factors hindering RP and remedies across different disciplines and sectors (RQ3).
- An exploratory survey of experts to gather views on:
  - a) perceptions of a decline in RP (RQ2);
  - b) factors potentially hindering RP and remedies to increase it across different disciplines and sectors (RQ3);
  - c) the potential for OS to increase RP (RQ5) and the social impact of research (RQ4).
- A workshop with experts to:
  - a) discuss the main results from the literature review and the survey, focusing on where they differ;
  - b) identify open questions that are not addressed by the literature review or identified by survey participants;
  - c) discuss the main policy recommendations.

Also in the report, we provide ([1]):

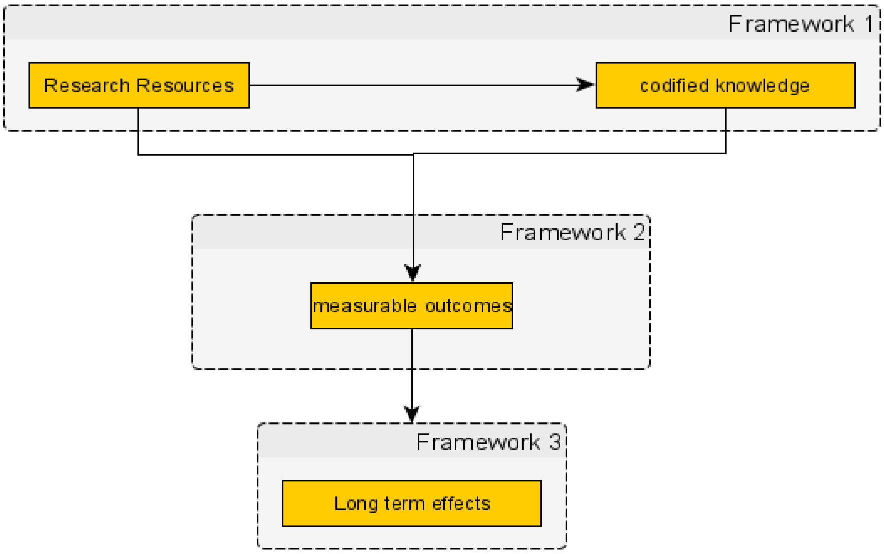
- the methods and results of the systematic literature review planned for task 1, define RP and identify and quantify the factors responsible for a decline in R & I productivity, and task 2, analyse possible remedies that contribute to increasing the productivity of the European Union (EU) R & I system (WP2.1 and WP3.1);
- a questionnaire used in a non-representative small-scale survey of key experts in the field;
- a summary of the final workshop with experts (in Annex 6).

The **literature review** is based on the methodology described in the inception report, with modifications to reflect the comments received from the European Commission after the interim meeting held on 22 March 2021.

The literature review was performed in two phases. During the first phase (months 2–4), we identified and surveyed scientific papers that discussed RP, with the aim of organising them around distinct definitions of RP. The results from this review showed that the literature can be classified into three main frameworks that address different aspects of RP, and focus on different stages of the R & D process. These are framework 1, the **scientometric framework**; framework 2, the **innovation framework**; and framework 3, the **societal impact framework**.

([1]) The authors have contributed as follows to the various sections: Tommaso Ciarli (Sections 1–3), Diego Chavarro (Sections 1–3), Valeria Arza (Sections 1–3), Hugo Confraria (Sections 1–3), Robbin te Velde (Annex 6) and Max Kemman (Annex 6). Alessandro Muscio was the project manager and quality reviewed all deliverables.

Figure 6. Three main frameworks addressing RP



After discussing the features, content, focuses and relevance of these three frameworks with the Commission, we decided to focus on framework 2 (innovation framework), where RP is defined as **the ratio of research inputs (e.g. funding and human capital) to innovation outputs (e.g. technologies, patents, ideas and solutions to problems)**.

In the second phase (months 5–6) we identified and reviewed literature relevant to framework 2, with the aim of studying:

- the extent to which it identifies a decline in RP;
- the hindering factors that explain this decline;
- the remedies proposed to improve RP.

We found two corpora of literature. The first concerned the production of innovations, in some cases measured with patents, but more often measured with other innovative outputs. The second concerned the role of R & D in total factor productivity, or other outcomes (e.g. reducing pollution) through innovation. Although studies in both corpora analysed how RP can be improved, it is mainly the first corpus that was concerned with a potential decline in RP. We found that 32 % of the papers reported a decrease in RP, while only 5 % reported an increase. The majority of the papers do not address this issue, but some identify hindering factors and suggest remedies to increase RP. The factors that may hinder RP and potential remedies differ substantially across papers. To analyse the main hindering factors and remedies we grouped them into categories and subcategories. We find that most hindering factors are related to specific R & D routines and processes, business and scientists' incentives to focus on narrow areas of research, and furthering the endless frontier of knowledge needed for innovations. These factors require different remedies. For instance, incentives may be improved by changing R & D routines, through governance of funding, and by steering R & D priorities towards more high-risk and radical research. In the report we provide a detailed summary of those categories, but interventions should focus on specific remedies, based on the careful consideration of the specific R & D processes that need to be improved: there seems to be no silver bullet to improve RP.

Following the inception report, we performed a **small-scale** survey consisting of exploratory questions to interrogate experts on the main obstacles to and remedies for RP. As only a small subsample of the literature surveyed discusses OS as a potential remedy, the survey questions focused particularly on OS, and explicitly asked the experts which OS practices may improve RP. It also interrogated experts on the relationship between RP, OS and the social impact of RP.

We first performed a pilot of the survey with 10 experts, in July 2021, to develop a final questionnaire (Annex 4).

The survey was conducted from 22 July until 6 September 2021. It was sent to 421 potential respondents, including experts identified through the literature review, contacts at the European Commission, contacts of the research team, research council managers and members of peer review colleges. We gathered 52 responses (12 % response rate) from experts from the social sciences (62 %), natural sciences (29 %) and multidisciplinary (9 %) backgrounds. Most respondents were based in research institutions and universities (75 %), with some from the public sector (15 %) and the private sector (10 %). Most respondents were from Europe, but experts from different regions of the world were represented. We organised answers over three main topics: (i) perceptions on the decline of RP and the main hindering factors and remedies; (ii) the role of OS in addressing the main hindering factors, or reducing RP; and (iii) the role of OS in increasing the social impact of RP.

The results show that, in contrast with the literature, respondents were more inclined to agree that RP has increased in the last 10 years (58 %), while breakthroughs have remained stable (31 %). This may suggest that the 'value' of research outputs has decreased because breakthroughs have not followed the increase in RP, but respondents did not connect such decline to RP.

Respondents identified the following hindering factors: evaluation pressure / incentives (46 %); R & D management (38 %); cost (29 %); regulation (19 %); and human capital (12 %). To a lesser extent, respondents also pointed out collaboration issues (10 %), siloed knowledge (10 %) and path dependence (10 %). The relative importance of the hindering factors mentioned by the respondents is not too different from the findings from the literature, with one relevant exception: there is very little mention of market pressures and the ever-expanding knowledge frontier. Moreover, we find that the respondents emphasised evaluation pressure and R & D management issues more than the literature.

Alongside the main hindering factors, the main remedies identified by respondents emphasised the need to change research evaluation systems (38 %), increase public funding (25 %), improve and develop new policy instruments (25 %), reconfigure firm management (21 %) and foster open access (19 %). To a lesser extent, respondents also pointed out remedies related to R & D management (13 %), collaboration (13 %) and human capital (13 %). Overall, the literature and the survey coincide in focusing on improving R & D routines. However, new methods, technologies and OS – except for open access – were not mentioned by the respondents.

The section on OS attempted to encourage respondents to reflect on these practices, which do not get much attention in the literature. Respondents were positive about the role of OS practices in RP. Most of them (96 %) identified at least one OS practice as potentially relevant to increasing RP. In particular, interdisciplinarity was identified as relevant by the most respondents (79 %), followed by operationalising FAIR data principles (75 %), and documenting and sharing workflows and methods openly (75 %).

Based on insights from the literature review, and the discussion with experts involved in the pilot, the survey also included a more critical question to assess whether or not OS practices could hinder RP. The majority of respondents (63 %) also believed this was not the case. Given the option to include any of the OS practices among those that may hinder RP, some respondents indicated open licences (12 %), operationalising FAIR data principles (12 %) and interdisciplinarity (12 %).

The majority of respondents (83 %) considered that OS can help to overcome the two main hindering factors that they indicated in their earlier response. They considered that OS practices contribute to solving issues related to the fast-expanding endless frontier of knowledge needed for innovations, the complexity of knowledge combination, and issues of R & D incentives and R & D routines. Some 63 % of respondents also provided examples for the potential of OS to improve RP through improving research efficiency (e.g. open data reduces the costs of data collection), increasing research quality (e.g. replication is facilitated); problem solving (e.g. research questions are better informed by societal needs); creating awareness (e.g. scientists learn new methods or identify new collaborators, or the public's perception of science is improved) and improving communication (e.g. scientific results are communicated faster). Importantly, 90 % of respondents considered that at least one OS practice could contribute to a large or very large extent to increasing the societal impact of research.

We concluded the project with a **final workshop** (see Annex 6). In preparation for this workshop, we conducted a number of exploratory interviews in three sectors: (i) microchips, (ii) agriculture and (iii) biofuels. The objective of the interviews was to further understand the definition of RP, perceptions of the decline in RP, and hindering factors and remedies. Findings from the three sectors yielded noticeably different results. This suggests the need for a sector- and/or technology-specific approach to increasing RP, as also suggested by the results of the literature review and the survey. Other important takeaways from the interviews were as follows.

- At least in microchips, the assumed decline in RP is largely due to increasing inputs (and therefore not in declining outputs), and these inputs may actually relate to unmeasured publicly funded research inputs at the onset of this process.
- Research cannot take place without manufacturing (therefore, an erosion of the manufacturing base eventually slows down RP).
- Funding is needed for ideation. At least in biofuels, the bottleneck is in developing scientific ideas further, and this is entirely due to a lack of funding.
- In agriculture, while funding has declined, return on investment in agriculture research (in terms of crop yield) has remained stable (therefore, RP has actually increased when measured in output/input). Funding has effectively declined in part because a lot of resources are spent on administering these resources, rather than on research per se (i.e. administrative burden has increased).
- The primary role of government is to lead, that is to guide socioeconomic developments in new directions. This requires bold choices in terms of policymaking and regulation, and a long-term government.

The final workshop was held online on 21 September 2021. Eight international experts participated in the workshop, and several experts from the Commission (the Directorate-General for Research and Innovation and the Joint Research Centre) participated as observers.

In the first session of the workshop, the results of the systematic review and survey were discussed. The experts worried that the definition of RP used in the project (i.e. research inputs in relation to outputs) may introduce a bias against high-risk and radical innovations. Moreover, the innovation-based definition makes the discussion of RP politically fragile, as policies to increase successful outputs may limit the extent to which output is truly innovative. Finally, a focus on quantity may also disproportionately shift policy attention to research fields with a stronger culture of increased outputs, away from fields that require more time to produce outputs, reducing the macroeffectiveness of the R & I system.

In the second part of the workshop, six provocations were discussed. The first three provocations focused on RP, and the latter three focused on OS.

Key issues that were mentioned with regard to RP are as follows.

- Radically innovative research inherently implies inefficiency.
- The ultimate impact of research in terms of socioeconomic benefit may be too distant in time and difficult to attribute to the original research.
- The body of knowledge to which science contributes is increasingly large and therefore increasingly difficult to build on. However, moving between very different lines of research may still boost RP.
- Although science at large may not be less productive per se, the impact of the organisation of science on productivity is problematic (especially if the current evaluation system is aimed at benefiting society, as societal stakeholders are seldom in close contact with research proposals).

Key issues that were mentioned with regard to OS are as follows.

- OS may have downsides at individual level (at least in the current institutional setting), but is still beneficial to the R & I system as a whole.
- It may prevent erroneous or fraudulent behaviour, and may also increase the replicability of research (which positively impacts RP).
- Increasing the transparency of research will eventually increase the public's trust in science and scientific results. However, brokering and translating research to societal actors may impede RP as more activities are undertaken that do not directly lead to increased outputs.
- OS leads to decreased productivity in the short term, as an increased portion of input into the R & I system is required for factors that do not directly lead to outputs in the short term.

In the final session, four potential policy options to improve RP were discussed:

- increasing resources for R & D
- changing research funding priorities
- changing research evaluation practices
- OS policies.

The experts noted that the first three options are strongly related, and that all four options are too strongly top-down, with bottom-up practices to improve RP lacking. To this end, a fifth scenario 'changing the research system' was proposed, aimed at not only individual researchers but also research institutes as employers of researchers. Without this fifth scenario, it may not even be possible to successfully pursue the second, third and fourth scenarios. However, when research institutes do not desire changes to the research system, policy interventions may not prove successful.

The final sections of this report briefly discuss the findings across the different research activities, in relation to new evidence on the extent to which research conducted and published in the EU is related to the sustainable development goals (SDGs). We then suggest five policy recommendations.

1. Literature review

1.1. Methodology

As agreed in the inception phase, our methodology for the literature review included three main steps, namely:

1. a review of definitions of RP and frameworks according to the literature;
2. a discussion with the European Commission to ensure a focus on the most relevant frameworks;
3. a review of hindering factors and remedies within the selected framework according to the literature.

The general approach to the two reviews (steps 1 and 3) followed the steps outlined in the inception report, namely:

1. setting the research questions;
2. selecting the sources and databases, which for the two reviews consisted of a set of seed literature in Scopus;
3. specifying inclusion criteria, which was based on the relevance of the papers to the research questions of the project;
4. defining search strings, which was done to comprehensively represent the research questions;
5. screening the papers, which included the following stages:
    a) one reviewer reading titles and abstracts
    b) other members of the team performing a second review
    c) resolving discrepancies through discussions between reviewers
    d) reading the full text of the papers;
6. classifying evidence for analysis, using classification matrices for the list of papers reviewed, with fields describing the papers in terms of bibliographical information, assessment of relevance, and fields specifically related to definition of RP, inputs, outputs, hindering factors and remedies;
7. applying thematic analysis, in which the classifications were further refined and interpreted through discussion between the team members.

The discussion (step 2) included a meeting and email exchanges. During the meeting the research team presented the three main frameworks identified, their main properties and frequencies, and their relationship with the societal impact of research. Based on this information, the framework for the second part of the literature review was agreed. The team performed a second literature review on this framework to systematise papers according to their definition of productivity (within framework 2), hindering factors and remedies. In the following sections we describe in more detail the procedure of the three main steps conducted in this literature review.

1.1.1 Defining research productivity

The research team conducted a systematic literature review to analyse how scholars define RP. The review was guided by the following two main questions.

- How is RP defined in the literature?
- How can different definitions be grouped into different theoretical and empirical frameworks?

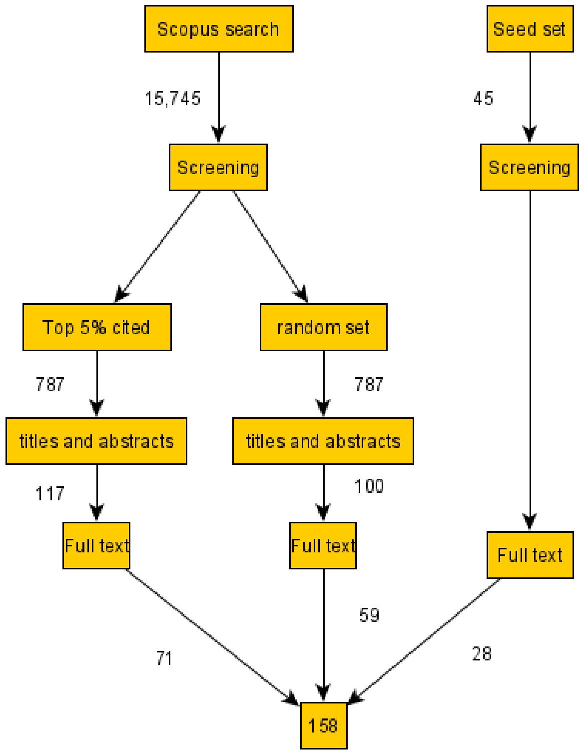
Based on several preliminary basic searches and seed papers (seed set in Figure 7) suggested by the Commission and the research team, we used the following search string to search for papers in Scopus:

(TITLE-ABS-KEY ((‘research productivity’ OR ‘scientific productivity’ OR ‘research evaluation’ OR ‘research performance’ OR ‘academic impact’ OR ‘research impact’ OR ‘scientific impact’ OR ‘research outcome’ OR ‘research output’))) AND PUBYEAR > 1951 AND PUBYEAR < 2021 AND (LIMIT-TO (DOCTYPE, ‘ar’) OR LIMIT-TO (DOCTYPE, ‘re’))

We found 15 745 papers in Scopus. Given the large number of papers, we selected the top 5 % most cited papers, by year. To avoid biases due to citation practices in different disciplines, we selected an equal number of papers (N = 787) at random from the remaining 95 % of papers. We performed an initial screening of titles and abstracts of papers in both sets, plus the seed set, and selected the papers relevant to defining RP and its impact on economies and societies. We selected 217 papers from this first screening and performed a full-text screening of the papers. In total, we classified 158 papers. Figure 7 summarises the procedure for selecting relevant papers, with the number of papers selected at each step.

For each paper, we extracted the following information manually: (i) the RP framework to which we allocated papers; (ii) the inputs of research; (iii) the outputs of the research; (iv) the definition (implicit or explicit) of RP based on the use of inputs and outputs; (v) whether or not they identify outcomes beyond the research practice; and (vi) whether or not they identify/define breakthroughs.

Figure 7. Sample and selection of the relevant papers to identify frameworks



The framework refers to the general approach followed by the papers to study RP. This field was used to cluster the records. By inputs we mean the resources used in the R & D production process. By outputs we mean the results of the R & D process. For the definition of productivity, we either identified the explicit definition used or inferred the implicit definition from the inputs and outputs. We identified outcomes as the results of research other than publications. We identified breakthroughs if they were mentioned and defined explicitly in the papers. We also performed a cluster analysis based on bibliographical coupling and text similarity to test our classification of the frameworks.

1.1.2 Selecting the most relevant framework

The first exercise yielded a set of definitions and frameworks that were presented by the research team in a meeting with the Commission on 22 March 2021. During this meeting, there was a discussion on the relevance of the different frameworks to the interests of the Commission.

1.1.3 Examining hindering factors and remedies

Focusing on the literature in framework 2 we conducted a systematic literature review to identify evidence of a decline in RP, factors that may hinder RP and potential remedies. The search of the literature and the analysis were guided by the following questions.

- What are the different definitions of RP and what inputs, outputs and outcomes do they consider?
- Does the literature identify a decline in RP? Does the literature identify a decline in any particular sector? Does the decline differ depending on how RP is defined?
- What are the main hindering factors and remedies? Are they different between definitions/sectors?
- Are there mentions of breakthroughs in the literature?

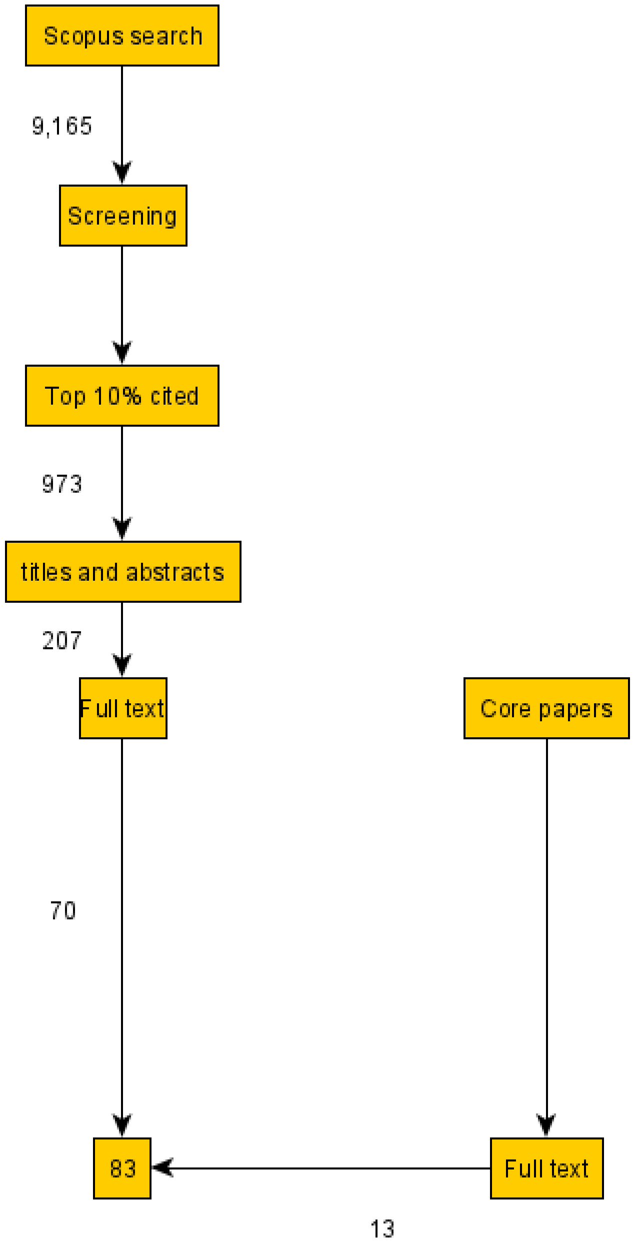
Based on several preliminary searches of the literature and the identification of core papers suggested by the Commission and the research team, we defined the following search string to search for papers in Scopus:

TITLE-ABS-KEY ((‘research’ OR ‘science’ OR ‘R & D’) AND (‘techn* progress’ OR ‘techn* change’ OR ‘techn* advanc*’ OR ‘techn* frontier’ OR ‘breakthrough*’ OR ‘innovat*’ OR ‘invent*’) AND (‘productiv*’)) AND (LIMIT-TO (DOCTYPE, ‘ar’) OR LIMIT-TO (DOCTYPE, ‘re’))

The search was designed to capture the research activity (‘research’ OR ‘science’ OR ‘R & D’), its outputs or outcomes (‘techn* progress’ OR ‘techn* change’ OR ‘techn* advanc*’ OR ‘techn* frontier’ OR ‘breakthrough*’ OR ‘innovat*’ OR ‘invent*’) and how efficiently they were delivered (‘productiv*’).

We found 9 165 papers in Scopus. Two research team members screened the titles and abstracts of the top 10 % papers by citation (per year) to select those potentially relevant to the analysis (207). In addition, we selected 10 papers from the first literature review to add to the sample (core papers in Figure 8). After manually reviewing the 207 papers, we manually screened the text of the 83 selected papers. Figure 8 summarises the procedure, with the number of papers selected at each step. We selected all papers that either analysed or discussed RP, using very different methods (such as linear probability models, econometric approaches to identify causal relations, descriptive statistics and case studies). Therefore, the results are based on a mix of evidence that includes causal relations, conjectures and in-depth explanations based on a single observation. They are aimed not at providing a meta-analysis of RP decline, hindering factors and potential remedies but at illuminating the current view in the literature, with some views supported by causal analysis and some by in-depth studies.

Figure 8. Sample and selection of relevant papers defining RP, and detailing hindering factors and remedies (framework 2)



We classified the 83 papers according to eight dimensions of analysis: inputs, outputs/outcomes, definition of RP, decline in RP, breakthroughs, hindering factors and remedies. We also collected data on the sector of study, level of analysis, year of study and methods.

Inputs refer to the resources used in the R & D process. Outputs and outcomes refer to the results of the R & D process in terms of innovations or more long-term outcomes. The productivity definition either implicit or explicit refers to the kind of output/outcome studied. Breakthroughs were identified when explicitly mentioned in the papers. Decline in RP report whether the paper finds a decline or an increase in RP. Hindering factors report factors identified by the authors as having a negative impact on RP;

we also identified the hindering factors as the complement of factors identified as increasing RP. Remedies report factors associated by the authors with an increase in RP (or limiting the decline).

1.2. Results

Firstly, in Section 1.2.1 we provide the results of our analysis of definitions of RP across 158 papers (see Figure 7) and present the three overarching frameworks identified. Secondly, in Section 1.2.2, we focus on framework 2 – the innovation framework – for which we performed an additional search and identified a set of 83 relevant papers (Figure 8) to analyse RP decline, factors hindering RP and remedies related to this framework.

1.2.1. Research productivity frameworks

To identify definitions and frameworks of RP analysed in the literature, we categorised the papers according to their inputs and outputs/outcomes. Crucially, definitions of RP must refer, implicitly or explicitly, to inputs and outputs or outcomes of research. In the context of this study, definitions of RP also considered the impact on the R & I system/society, and possible societal challenges.

Table 1 shows a synthesis of the inputs, outputs, outcomes and breakthroughs used by the papers to define and analyse RP.

Table 1. Synthesis of variables that define productivity

Definition of RP	Inputs	Outputs	Outcomes	Breakthroughs
Publication based Citation based Altmetrics based Patent based Funding based Impact focused	Macro Individual Research focus Collaborations Other outlets Tools Organisation Research funding	Publications Citations Patents Altmetrics Funding Innovations Other non-academic Technologies Recognition Access to resources Human capital	Scientific Public engagement Addressing challenges Economic Individual Innovations H-index Contribution to relevant topics	Scientific Citation based Patent based Radical innovations and inventions Substantial societal impact

Outputs and outcomes differ substantially across different corpora of literature, whereas inputs are not specific to any particular corpus of literature. We identified three main corpora, according to output and outcomes, and the related definitions of RP.

The first corpus studies the ratio of research inputs to the number of publications/citations produced or received by a certain author, institution or region. This corpus is very homogeneous and is driven by data availability.

The second corpus attempts to measure the ratio of research inputs to academic non-bibliographical outputs or economic (sometimes societal) outcomes. This corpus is more heterogeneous because the outputs and outcomes can differ substantially.

The third corpus studies the relationship between research inputs and the societal impacts (outcomes) of research. This corpus is even more heterogeneous, reflecting the variety of impacts as well as channels through which research may have an impact on society.

Based on the sampled studies, we classified the three corpora according to frameworks focused on assessing RP.

1. **Scientometric framework (framework 1).** The literature in this framework explicitly defines RP as the ratio of research inputs to knowledge codified in bibliographical outputs: scientific publications or patents. The main aim of the research in this framework is to assess the efficiency of publishing or patenting. The assumption is that more publications and patents is better. The impact of this codified knowledge on societies is usually evaluated using normalised measures of citation impact (number of citations per publication controlling for year/field).
2. **Innovation framework (framework 2).** The literature in this framework is more heterogeneous than framework 1 and implicitly (and less frequently explicitly) defines productivity as the ratio of research inputs (e.g. funding and human capital) to innovation outputs (e.g. technologies, patents, ideas and solutions to problems). The main aim of the research in this framework is to assess the efficiency of research funding to innovate, mainly leading to economic growth or productivity. In a few cases, papers explore other broader outcomes, but the connection between innovation and societal outcomes is often loose and assumed.
3. **Societal impact framework (framework 3).** The literature in this framework is far more heterogeneous than both framework 1 and framework 2, and is rarely framed as research efficiency. Productivity is defined only implicitly, as the relationship between research inputs, how they are organised and prioritised, and their potential effects on society. The main aim of the research in this framework is to improve the way in which research is done to achieve more and better societal outcomes. Outcomes can vary widely, and often no explicit measure of productivity is provided.

Tables 2–4 systematise the surveyed literature in the three frameworks. Annex 1 provides more details on the categories, examples and references used to build these tables. Figure 9 reports the share of papers per framework in our sample of the literature on RP.

Table 2. Systematisation of the scientometric framework (framework 1)

Example definition: 'the [scientific] output produced in a given period per unit of production factors used to produce it' (Abramo and D'Angelo, 2014)	
Inputs	**Outputs**
Research focus: disciplines; diseases; priorities or other subjects Individual: researchers; inventors Macro: research funding; HERD; GERD; GDP Organisation: mainly universities and research institutes Collaborations: co-authorships; interdisciplinarity; network analysis; social capital Other outlets: journals; journal twitter accounts Tools: ICT	Publications: journal articles; conference proceedings; books; magazines Citations: normalised citation impact; highly cited papers; impact factor Patents: patents per paper; patents per funds received Altmetrics: tweets per paper Funding: research opportunities; future funding
Outcomes	**Breakthroughs**
H-index Contribution to relevant topics	Scientific: citation based; patent based

NB: GDP, gross domestic product; GERD, gross domestic expenditure on R & D; HERD, higher education expenditure on R & D.

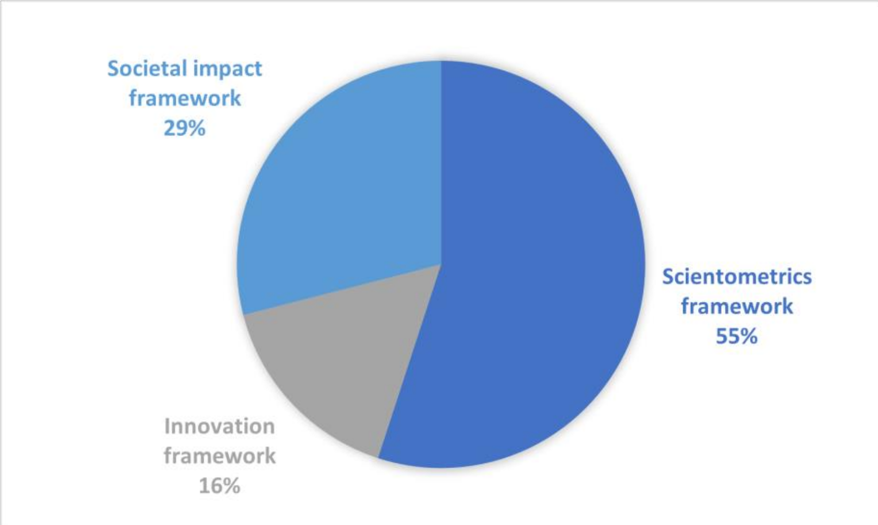
Table 3. Systematisation of the innovation framework (framework 2)

Example definition: 'flow of ideas divided by the number of researchers' (Bloom et al., 2020)	
Inputs	**Outputs**
Organisation: doctoral programmes; research team members; laboratory equipment Individual: researchers; talents Research focus: knowledge recombination Collaboration: citizen science Tools: ICT	Technologies: digital objects; biological specimens; data curation; service tools; patents Recognition: prizes Access to resources: grants Innovations: ideas; breakthroughs; efficiency
Outcomes	**Breakthroughs**
Addressing challenges: years of life saved from specific diseases; clean growth; the future of mobility Economic: economic growth; labour productivity; revenue; market capitalisation; employment Individual: leadership; career development Innovations: number of transistors packed onto an integrated circuit; crop yields; new molecular entities; drug discovery; drug development	Outliers: radical innovations; inventors

Table 4. Systematisation of the societal impact framework (framework 3)

Example definition (research effort defined implicitly): **'we define research impact as demonstrable and/or perceptible benefits to individuals, groups, organisations and society (including human and non-human entities in the present and future) that are causally linked (necessarily or sufficiently) to research' (Reed et al., 2021)**	
Inputs	**Outputs**
Research funding: implicit and explicit / R & D; funding source (private versus public) Organisation: university third stream activities Individual: researchers and their psychological characteristics Collaborations: collaborations with policymakers/stakeholders Scientific papers	Publications: coursebooks; syllabuses; commissioned reports; professional guidelines; newspapers; articles; blogs Patents Altmetrics: use of evidence in policy; social media Innovation: products; processes; design; images; spinoffs, exhibits, events; social innovations Human capital: skilled researchers
Outcomes	**Breakthroughs**
Scientific: stock of knowledge; transdisciplinarity quality; human capital (education); technological (new or improved technologies); cultural (contributions to society) Public engagement: policy documents; quadruple helix interactions Addressing challenges: social, economic and environmental indicators; health and well-being; contextual challenges; capabilities; economic Individual: capacity building	Scientific: discoveries with a major impact on society; citation based; patent based; innovation based

Figure 9. Percentage of papers per framework



An overview of the three RP frameworks immediately uncovers the multidimensional and multilevel character of RP, and how it is framed and analysed across different studies that have different aims and make different assumptions. Although input categories are similar, the focus of each framework is different. Even within frameworks, the level of analysis can be very different, with implications for the impacts of RP. Inputs, outputs and outcomes may be at individual, organisation, country and journal levels. The three frameworks focus on different aspects of RP, and this poses challenges to achieving one specific definition. For instance, there is a key difference between RP understood in the context of science and innovation and RP in the context of its impact on society. In the first case, the outputs and outcomes are related to the reputation of scientists, the use of knowledge in academia, new technological developments and economic benefits. In the second case, impacts range from the scientific to organisational and environmental.

1.2.2. Definitions of research productivity in the innovation framework (framework 2)

In the innovation framework, RP is broadly defined as the ratio of research inputs (e.g. funding and human capital) to innovation outputs (e.g. technologies, patents, ideas and solutions to problems). A higher RP implies an improvement in the efficiency of the research system or funding in generating/developing innovations that lead to socioeconomic benefits. Within this general definition we identify more specific definitions, in relation to the inputs, outputs and outcomes that researchers consider.

From the sampled literature in the innovation framework we identified the following four definitions of RP ([2]) (Table 5).

- **Economics based (45 %).** RP is broadly defined as the ratio of any research input to an economic outcome, such as firm productivity, profits, sales and value added.
- **Innovation based (40 %).** RP is broadly defined as the ratio of any research input to the number of innovations, such as new drugs, new molecular entities (NMEs), and new products or processes.
- **Patent based (12 %).** RP is broadly defined as the ratio of any research input to the number of patents as a measure of innovation.
- **Impact based (6 %).** RP is broadly defined as the ratio of any research input to non-economic outcomes such as pollution, food security, patients' health and start-ups.
- **Not addressed (11 %).** These papers did not explicitly or clearly define RP.

Table 5. Definitions of RP in the innovation framework, and their inputs and outputs

Definition of RP	Input	%	Output	%
Economics based	Funding	31	Economic	47
	Knowledge	22	Innovation	15
	Human capital	12	Environmental	4
	Innovations	4	Health	3
	Business	1		
	Infrastructure	1		
Innovation based	Funding	30	Innovation	42
	Human capital	11	Economic	9
	Knowledge	11	Challenges	1
	Infrastructure	4	Environmental	1
			Health	1
Patent based	Human capital	9	Patents	12
	Funding	5		
	Infrastructure	1		
	Knowledge	1		
Impact based	Funding	5	Economic	4

([2]) One paper can refer to different definitions. Percentages are based on 83 papers.

	Human capital	1	Health	3
	Knowledge	1	Innovation	3
			Challenges	1
			Environmental	1

NB: Only papers with a definition and at least one input or one output are taken into account in this table (74 papers in total).

The definition of RP reflects the main focus of the papers reviewed, but it is possible, and not infrequent, that papers in a given definition consider the relationship between R & D and several outputs/outcomes. This reflects the not so neat distinction between, for example, innovation and economic outcomes; consider, for example, the relationship between innovation and firm productivity. This explains why, for example, in the innovation-based definitions of RP several papers also study the economic impacts.

The economics-based and the innovation-based definitions are the most commonly studied in our sample, making up approximately 83 % of all sampled papers. The impact-based and the patent-based definitions appear each in less than 10 % of the studies in our sample. This is expected given the focus on the innovation framework, which is less concerned with the social impacts (framework 3) but tends to study the ratio of inputs to outputs beyond knowledge/bibliometric outputs (framework 1).

The four definitions are similar with regard to the inputs analysed in the papers, with funding, knowledge and human capital the most frequent across all definitions ([3]). Funding is the most studied input in both the economics-based and the innovation-based definitions of RP, but knowledge-related inputs are more relevant to the economics-based definition. However, this may be an artefact of the literature sampling strategy.

1.2.3. Analysis of research productivity decline

We identified all papers that explicitly reported or analysed a decline, or an increase, in RP, by definition (Table 6) and by sector studied (Table 7). Around 32 % (27) of the 83 sampled papers report a decline, whereas only 5 % (4) reported an increase in RP. The majority did not report/study the decline in RP, although they studied how RP could be boosted to improve innovation, and economic or other outcomes ([4]). The temporality of the decline studied varies, with some papers taking a historical view

([3]) For the composition of each of the input and output categories, please see Annex 2.

([4]) Among the 27 documents that discuss a decline in RP, some of them report results from other documents, not direct evidence (e.g. Mignani et al., 2016; Plenge, 2016). As previously noted, in this literature review we include documents that provide evidence and documents that discuss potential remedies, combining evidence from other documents.

(1900–2010), a few studying the research boom period (1953–1993), and the majority focusing on the years between the mid-1990s and 2010 ([5]). Based on our sample of the literature, this finding seems to suggest that the issue of declining RP has recurred over time, at least since the study by Machlup (1962), where he found a threefold increase in R & D expenditures per technical person between 1941 and 1958. The phenomenon of a decline in RP has attracted more attention recently, including in relation to secular stagnation (Gordon, 2016), the slowdown in labour productivity across several countries (Crafts, 2018) and the return of the Solow paradox in relation to digital automation technologies (Acemoglu et al., 2014; Brynjolfsson et al., 2017).

The studies most interested in the decline in RP define RP based on the number of innovations (**innovation based**) (Fortunato et al., 2018; Bhattacharya and Packalen, 2020; Hermosilla, 2021). Some papers that use the **economics-based** definition of RP mention the decline, but they are less interested in analysing it, because their focus is more on the effect of R & D on firm productivity (Audretsch and Belitski, 2020; Koutroumpis et al., 2020). Firm productivity is influenced by innovation and RP, but not exclusively. This is also related to the fact that studies that use the **innovation-based** definition focus mainly on research-intensive industries (Pisano, 2006; Wang et al., 2013; Sun et al., 2021), whereas those that use the **economics-based** definition focus on all manufacturing sectors (Aldieri et al., 2021; Woltjer et al., 2021).

([5]) The methods also vary. Some studies use econometric estimations, some are based on basic descriptions of the data and other case studies are more theoretical. The data used vary substantially, making systematic comparisons across these studies meaningless.

Table 6. Percentage of papers reporting changes in RP by definition (%)

Definition of RP	Decline	Increase	Not addressed
Economics based	12	2	30
Innovation based	17	1	23
Patent based	6	1	5
Impact based	5	0	1

NB: Percentages were calculated over the full sample of 83 papers. One paper may refer to more than one definition of productivity.

Most studies are cross-sectoral (Table 7). Examples include Capone et al. (2021) on the inventive capacity of cities, Brown et al. (2017) on the determinants of R & D in high-tech industries, Hall et al. (2013) on the impact of R & D on innovation and productivity in Italian firms, and Bloom et al. (2020) on the RP of new molecular entities, agriculture, ICT, health and firms.

The literature on RP decline is mainly focused on R & D-intensive sectors, where a decline is documented (Table 7). Most studies analyse the pharma (Garnier, 2008; Pammolli et al., 2011; Hermosilla, 2021), biomedical (Bowen and Casadevall, 2015) and biotech (Pisano, 2006) sectors, with only a couple of these finding an increase in RP (Pammolli et al., 2020) ([6]). There are a few interesting exceptions though, including papers on computers and electronics (6) (e.g. Ravichandran et al., 2017), chemicals (Lanjouw and Schankerman, 2004) and mining (Nagaraj and Farinato, 2016).

With regard to the sectoral focus, most of the papers discuss the decline in the discovery of new drugs or NMEs, or in some cases in the number of patents granted. A few of these papers define breakthroughs as relevant patents (Kortum, 1997), drugs or innovations (Cuatrecasas, 2006; Kissin, 2010). However, they do not specify how they differ compared with non-breakthrough innovations, patents or drugs.

More recently, Bloom et al. (2020) produced a comprehensive study documenting the decline in RP in several sectors since 1965. At micro level, they found a decrease in outputs relative to R & D inputs in terms of yield rates for agricultural products, new drugs placed on the market, years of life saved from cancer or heart disease per publication or clinical trial, or the density of computer chips. At macro level they also found that RP was in systemic decline by measuring total factor productivity trends. Their conclusion was that, given the current diminishing returns to R & D (fast-expanding endless frontier), 'the economy has to double its research

([6]) Annex 3 describes the sample used for this framework. Table 33 shows the concentration of studies in pharma and biomedicine.

efforts every 13 years just to maintain the same overall rate of economic growth'.

Table 7. Percentage of papers reporting changes in RP by sector studied according to the International Standard Industrial Classification of All Economic Activities (ISIC) at two-digit level (%)

Sector (*)	Decline	Increase	Not addressed
Cross-sectoral	10		27
Pharma (21)	22	2	11
ICT (26)	7		2
Not defined (**)	1		8
Agriculture (01–03)	1	1	5
Academia (72)	2		5
Chemicals (20)	1	1	1
Construction (41–43)			2
Mining (01–09)	1		
Textiles (13–15)			1
Machinery (28)	1		
Energy (35)			1
Consultancy (69–75)			1
Government (77–82)			1
Education (85)			1

NB: Percentages are calculated over the full sample of 83 papers.

(*) Numbers in parenthesis refer to ISIC Revision 4.

(**) 'Not defined' includes conceptual, theoretical, qualitative and discussion papers.

1.2.4. Factors hindering research productivity and potential remedies

Many studies that do not explicitly identify or mention a decline in productivity discuss factors that may negatively affect RP and/or potential remedies. In this section, we discuss the main hindering factors and remedies according to the literature reviewed, and whether or not they change depending on how RP is defined (within the innovation framework) and across sectors. We grouped the hindering factors discussed in the studies (sometimes more than one per study) into five categories, each composed of more detailed subcategories.

- **R & D routines.** Innovation processes and routines have changed substantially over time and vary across sectors. As new technologies and new organisations emerge, R & D processes need to adapt (see, for example, studies in the area of artificial intelligence (Cockburn et al., 2019) and the pharmaceutical industry (Henderson and Cockburn, 1996; Owens et al., 2014; Cobb et al., 2019).
- **Market pressure.** Incentives are often driven by profits and not the need to expand knowledge to improve social welfare (Wallace and Rafols, 2015; Sarewitz, 2016; Gold, 2021).

- **R & D incentives.** Aside from market pressures, several policies shape innovation incentives in ways that are not aligned with breaking new boundaries (Brown et al., 2017; Fortunato et al., 2018; Koutroumpis et al., 2020).
- **Fast-expanding endless frontier.** New knowledge is essential for innovations, but as the frontier expands new knowledge is more difficult to achieve and more investments and talents are needed (Bush, 1945; Kortum, 1997; Jones, 2009; Bloom et al., 2020).
- **Knowledge combination.** Although innovation is a process of knowledge recombination, and radical innovations tend to emerge from the combination of more different knowledge components, such combinations are risky and are increasingly difficult to produce (Ziman, 2000; Fleming and Sorensen, 2004; Arthur, 2009).

Details of the composition of each category and definitions of each subcategory can be found in Annex 2.

Table 8 shows the relevance of each hindering factor category across the four definitions of RP in the innovation framework. Studies that use the **innovation-based** definition (as noted, the most frequent in our sample, given the definition of the innovation framework) are mainly concerned with R & D incentives dictated by regulations and bibliometric evaluation systems (34 %) and by inefficient R & D routines (30 %) (Brown et al., 2017; Gold, 2021). They are also concerned about the constant expansion of the knowledge frontier (Pammolli et al., 2011), and the increasing costs associated with advancing knowledge for innovations (20 %) (van der Greef and McBurney, 2005). Although knowledge combinations are seen as less relevant, a considerable number of studies raise the issue of the need to specialise in a specific area, topic or discipline, which reduces the opportunities for path-breaking recombinations (16 %) (Pisano, 2006; Jones, 2009; Fortunato et al., 2018).

Table 8. Percentage of papers identifying main hindering factors by definition of RP (%)

Hindering factor / definition	Innovation based	Economics based	Patent based	Impact based
R & D incentives	34	18	5	0
Regulation	18	16	0	0
Evaluation pressure	11	0	0	0
IPR	5	2	5	0
R & D routines	30	16	2	9
Firm management	7	11	0	7
R & D process	18	2	0	2
R & D management	2	2	2	0
Closed science	2	0	0	0
Fast-expanding endless frontier	20	14	11	2

Knowledge frontier	5	9	7	0
Cost	14	2	0	0
Human capital	2	2	5	2
Knowledge combination	16	16	7	2
Siloed knowledge	11	9	2	2
Managing collaborations	0	5	5	0
Disciplinarity	0	2	0	0
Path dependence	5	0	0	0
Market pressure	11		2	5
Capitalism pressure	5	5	2	5
Competition	7	2	0	0

NB: Percentages are calculated over 44 papers that addressed hindering factors. IPR, intellectual property rights.

Studies using the **economics-based** definition of RP focus on similar hindering factors. As these studies mainly focus on the relationship between R & D and innovation at firm level, they are relatively more concerned with firm management than the R & D process. They are not concerned with the evaluation pressure, given their stronger focus in applied research, and less concerned about the cost than about increased funding.

In Table 9 we report the relevance of the different categories of hindering factors to the sectors studied in the sampled literature. Because of the strong focus of the literature in the pharmaceutical and biotech industries, differences between sectors are not very relevant. We note that pharma studies focus mainly on R & D incentives (34 %), R & D routines (39 %) and market pressures (30 %). More specifically, the main hindering factors discussed in studies on pharma are about regulation (Pammolli et al., 2011; Bowen and Casadevall, 2015), specific R & D processes that could be improved (Owens et al., 2014; Caputo et al., 2016), the increased cost of R & D (van der Greef and McBurney, 2005; Plenge, 2016), the strong specialisation of research (Bowen and Casadevall, 2015; Pammolli et al., 2020) and the increased competition in research (Gassmann and Reepmeyer, 2005; Pisano, 2006; Garnier, 2008) (7).

(7) These subcategories code together a wide array of factors, which are studied case by case. For example, regulations refer to trade, as well as tax credits, industry standards, or more specifically in the pharma sector drug testing, as well as intellectual property rights mechanisms or policy instruments to incentivise radical innovations. Increased costs refer to the capital (new technologies), the increased risk of innovation, financial burden, testing procedures, the rise in R & D costs in relation to a stable approval rate and the need to invest more funding to attain the same results, given the fast changes in the knowledge frontier. With regard to siloed knowledge, studies discuss issues related to a lack of interdisciplinarity, a lack of diversity, and siloed organizational structures, and increased specialisation in specific knowledge domains. Specific R & D processes refer to subsector-specific aspects of R & D, for instance in relation to open innovation practices, time, the involvement of patients, drug testing and the use of specific markers.

Cross-sectoral studies provide less information about hindering factors than pharma studies, possibly because of their wider scope. The hindering factor most frequently pointed out is the fast-expanding frontier of knowledge (18 %) (Habib et al., 2019; Bloom et al., 2020), followed by R & D incentives (14 %) (Brown et al., 2017; Gold, 2021). Compared with pharma studies, cross-sectoral studies tend to focus less on market pressures and the R & D process. However, they point out collaboration issues, which are not addressed in pharma studies (Belderbos et al., 2015; Capone et al., 2021). Pharma and cross-sectoral studies refer to most of the 16 hindering factors found in the literature (14 when taken together). The only two factors that are not mentioned in the literature focusing on pharma and cross-sectoral studies are disciplinarity, mentioned in literature in the agricultural sector (Griliches, 1958), and path dependence, mentioned in literature in the academic sector (Fortunato et al., 2018). The contribution of the literature that focuses on other sectors to explain hindering factors is negligible.

Table 9. Percentage of papers identifying main hindering factors by sector (%)

Hindering factors / sectors (*)	Pharma (21)	Cross-sectoral	ICT (26)	Acad (72)	Agr (01–03)	ND	Min (01–09)	Chem (20)	Mach (28)	Gov (77–82)
R & D incentives	34	14	9	2			7	2	2	
Evaluation pressure	5	5		2						
IPR	11	5	7					2	2	
Regulation	18	5	2				7			
R & D routines	39	9	2		2	2				2
Closed science	2									
Firm management	14	5	2							2
R & D management	2	5				2				
R & D process	20				2					
Fast-expanding endless frontier	23	18	5	2	2	5		2		
Cost	14	2								
Human capital	2	2		2		2		2		
Knowledge frontier	7	14	5		2	2				
Market pressures	30	5	7		2			2	2	
Capitalism pressure	20	5	7		2			2	2	
Competition	9									

Hindering factors / sectors (*)	Pharma (21)	Cross-sectoral	ICT (26)	Acad (72)	Agr (01–03)	ND	Min (01–09)	Chem (20)	Mach (28)	Gov (77–82)
Knowledge combination	16	9	2	5	2	2				
Managing collaborations		7	2							
Disciplinarity					2	2				
Path dependence				2						
Siloed knowledge	16	2		2						

NB: Percentages are calculated over 44 papers that addressed hindering factors. Numbers in parentheses indicate sectors at two-digit ISIC Revision 4 level. One paper may reference different issues within the same hindering factor and different hindering factors. ND, not defined; IPR, intellectual property rights.

(*) Only sectors that reference hindering factors are shown.

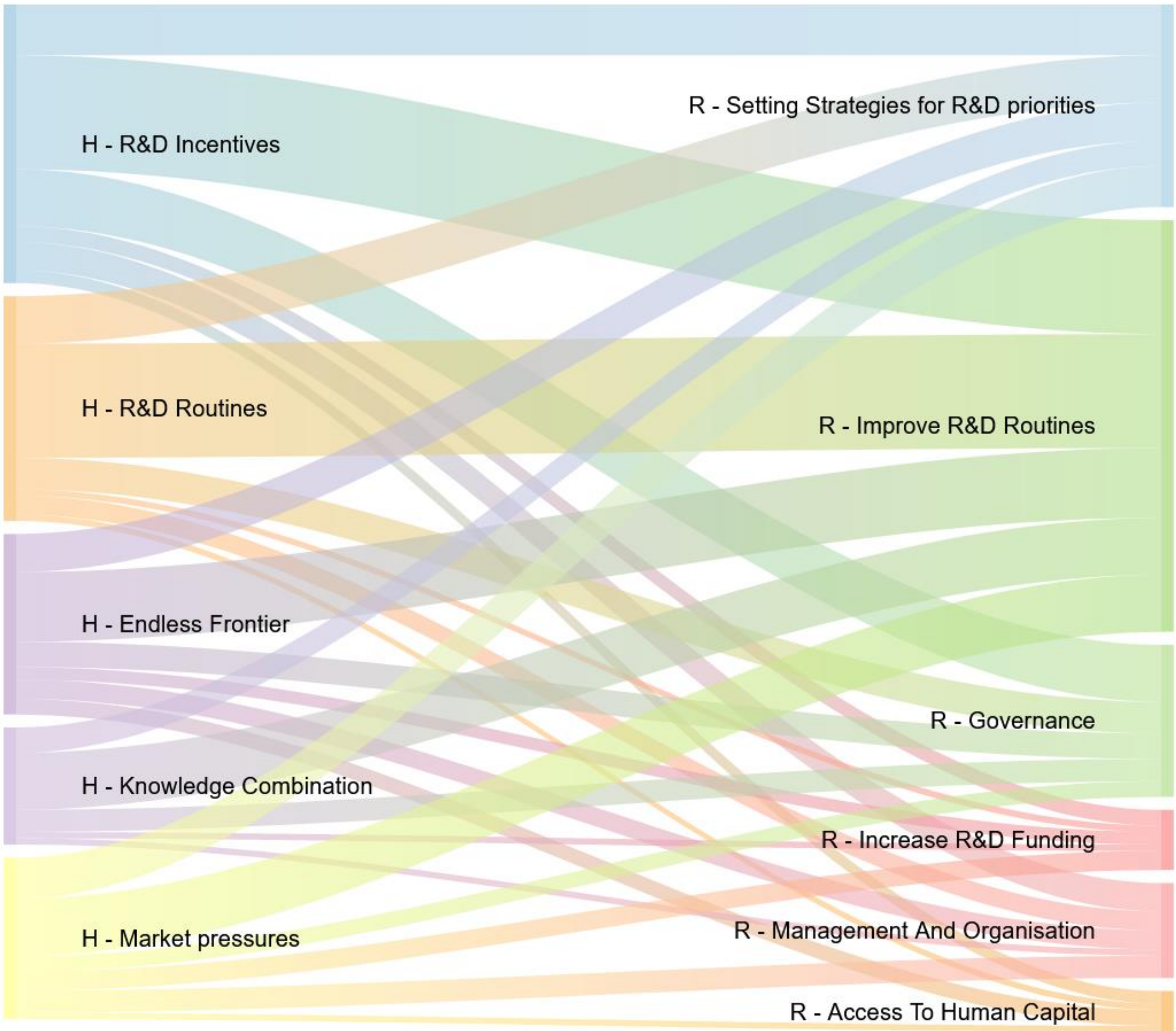
Beyond discussing factors that may constrain RP productivity, or cause its decline, some studies also propose, implicitly or explicitly, potential remedies to increase RP. As for the hindering factors, we grouped them into six categories, each composed of more detailed subcategories.

- **Improving R & D routines.** Specific aspects of R & D processes can be improved to combat hindering factors in various ways. These include using new technologies and methods (Pammolli et al., 2020), providing open access and improving reproducibility (Gassmann and Reepmeyer, 2005; Bowen and Casadevall, 2015), and improving collaboration (Baba et al., 2009; Belderbos et al., 2015).
- **Improving governance.** Several hindering factors could be addressed with better policies, such as intellectual property rights (IPR) (Brown et al., 2017; Habib et al., 2019), better regulations and several policy instruments to steer incentives (Pamolli et al., 2020; Bowen and Casadevall 2015; Pamolli et al., 2011; Garnier 2008;).
- **Improving management and organisation.** Beyond R & D processes, improvements could be made in the management and organisation of research-intensive organisations and their research labs (Paul et al., 2010; Cummings and Knott, 2018).
- **Setting strategies for R & D priorities.** To combat hindering factors that push for increased specialisation and siloed knowledge, there are several ways to modify the incentives of organisations and scientists to reduce (or increase) specialisation (Cuatrecasas, 2006); reduce the focus on bibliometric evaluations (Bhattacharya and Packalen, 2020); and increase the focus on diversification (Kissin, 2010), paradigm shifts (van der Greef and McBurney, 2005; Jones, 2009) and the societal impact of R & D (Hoos et al., 2015).
- **Increasing R & D funding.** Remedies in this category increase private or public funding to counteract the diminishing returns of knowledge production (Henderson and Cockburn, 1996; Raymond et al., 2015; Bloom et al., 2020).
- **Improving access to human capital.** Different strategies can be used to improve access to or the retention of skills and talents in R & D (Habib et al., 2019; Goel and Göktepe-Hultén, 2021).

Details of the composition of each category and definitions of each subcategory can be found in Annex 2.

Studies usually refer to more than one remedy for each hindering factor, or to one remedy that could address several hindering factors. They may point to specific processes, or to policies that would improve them. There is therefore not one relationship between hindering factors and methods, but a variety of remedies that have been proposed to address each hindering factor. Figure 10 maps the relationship between categories of hindering factors and categories of potential remedies. Relationships between hindering factors (left) and remedies (right) are computed based on papers that mention at least one hindering factor and one remedy.

Figure 10. Sankey diagram of hindering factors and remedies



NB: The size of each category is determined by the number of relationships, rather than by the number of papers.

For hindering factors related to specific **R & D routines**, studies discuss not only improvements in those routines, as expected, but also governance and changes in R & D priorities (Bowen and Casadevall, 2015; Du et al., 2019).

Improving the **governance** of the research system is also discussed as a potential remedy in relation to hindering factors related to **R & D incentives**.

For hindering factors related to **R & D incentives**, studies also suggest several remedies related to **improving R & D routines**, and **setting strategies for R & D priorities** (van der Greef and McBurney, 2005; Hermosilla, 2021).

Improving R & D routines is also the main category of remedies to improve hindering factors related to **knowledge combination** (Henderson and Cockburn, 1996; Garnier, 2008), although improving the **governance** of the research system and **setting strategies for R & D priorities** are also discussed as remedies in these cases.

To address hindering factors in the **fast-expanding endless frontier** and **market pressures** categories, studies mainly suggest remedies related to **improving R & D routines** (Fortunato et al., 2018) and **setting strategies for R & D priorities** (Jones, 2009). They also mention **improving access to human capital** (Habib et al., 2019).

Table 10 shows the relevance of each remedy category across the four definitions of RP in the innovation framework. A large number of studies using the **innovation-based** definition (the largest group in the innovation framework) focus on specific R & D routines (56 %), including R & D management (12 %) (Du et al., 2019); adopting new methods (12 %) and R & D processes (12 %) (van der Greef and McBurney, 2005); and open access (10 %) (Gassmann and Reepmeyer, 2005; Bowen and Casadevall, 2015; Mignani et al., 2016). To a much lesser extent, papers using the **innovation-based** definition consider remedies in relation to firm organisation and management (8 %) (Gassmann and Reepmeyer, 2005), changing strategies for R & D priorities by reducing the incentives linked to exclusively bibliometric research evaluation practices (6 %) (Bhattacharya and Packalen, 2020), policy instruments (8 %) such as mechanisms to ease the approval process of new therapeutics by public health organisations (Bowen and Casadevall, 2015) and increased public and private funding (12 %) (Garnier, 2008) ([8]).

For studies using the **economics-based** definition, firm management and organisation (16 %) and governance (18 %) are as relevant as specific R & D routines (20 %) (mainly R & D management and new methods).

([8]) Like the hindering factors, a wide variety of very specific remedies form the different categories. For example, remedies related to R & D management include increased variety (Pammolli et al., 2020), improved planning and optimisation of production (Brown et al., 2017), increased involvement of scientists in decision-making (Garnier, 2008), better trained chief executive officers (Cummings and Knott, 2018) and increased innovation time (Bowen and Casadevall, 2015). These remedies are also related to improved firm organisation, which include issues such as outsourcing part of the R & D process, which requires managing diverse teams (Gassmann and Reepmeyer, 2005). In relation to methods, remedies are even broader, ranging from new ways of breeding plants (Cobb et al., 2019), to the use of artificial intelligence (Serban and Lytras, 2020), and the use of *in vivo* systems (van der Greef and McBurney, 2005). Similarly, specific R & D processes include improving the relevance of drug tests (Plenge, 2016), including patients in R & D (Hoos et al., 2015), reducing the size of scientists' teams and more systemic approaches (van der Greef and McBurney, 2005).

Only three studies explicitly considered open access as a priority remedy, and these are almost exclusively among those using the **innovation-based** definition. In relation to this, it is important to note that only one paper in the whole sample focused on exploring OS as a more encompassing framework than open access to improve productivity (Gold, 2021). Similarly, few studies discussed the advantages of promoting interdisciplinarity, improving collaboration, diversification or other forms of breaking knowledge silos.

Table 10. Percentage of papers reporting main remedies by definition of RP (%)

Remedy/definition	Innovation based	Economics based	Patent based	Impact based
Improving R & D routines	56	20	18	12
Collaboration		4	6	
New methods	12	6		2
Open access	10		2	
Interdisciplinarity	6			
R & D management	12	6	6	8
R & D organisation	2		2	
R & D process	12	2		2
Technologies	2	2	2	
Improving management and organisation	12	16	2	8
Firm management	2	6		
Firm organisation	8	8		6
Market strategies	2	2	2	2
Improving governance	12	18	0	2
IPR protection		4		
Policy instruments	8	6		2
Regulation	4	8		
Setting strategies for R & D priorities	16	6	2	8
Diversification	2	2		
Incremental innovation		2		2
Paradigm shift	4	2	2	
Research evaluation	6			
Social impact orientation	2			4
Specialisation	2			2
Increasing R & D funding	12	10	4	2
Private funding	6	6	2	
Public funding	6	4	2	2
Improving access to human capital	8	4	4	2
Human capital	6	4	2	2

Remedy/definition	Innovation based	Economics based	Patent based	Impact based
Inclusion	2		2	

NB: Percentages are calculated over 52 papers that addressed remedies.

Table 11 shows the relevance of the different categories of remedies across the sectors studied in the sampled literature. Whereas the hindering factors discussed in pharma studies are spread relatively equally across categories of hindering factors (Table 8), there is a much stronger focus with regard to remedies on the improvement of R & D routines (63 %).

Table 11. Percentage of papers reporting main remedies by sector (%)

	Pharma (21)	Cross-Sectoral	ICT (26)	Chem (20)	ND	Acad (72)	Agr (01–03)	Min (01–09)	Mach (28)
Improving R & D routines	63	10	10	6	6	4	2	2	2
Collaborations	6	4	4	6					2
New methods	10				2		2	2	
Open access	10		2						
OS		2							
Interdisciplinarity	2					2			
R & D management	17	4	2		2	2			
R & D organisation	4								
R & D process	12								
Technologies	2		2		2				
Improving management and organisation	19	8	0	2	0	0	0	0	0
Firm management	2	6							
Firm organisation	13	2							
Market strategies	4			2					
Improving governance	12	12	2	0	2	0	0	0	0
IPR protection		4							
Policy instruments	4	4	2		2				
Regulation	8	4							
Setting strategies for R & D priorities	26	2	0	0	0	0	0	0	0
Diversification	4								
Incremental innovation	4								
Paradigm shift	4	2							
Research evaluation	6								
Social impact orientation	4								
Specialisation	4								
Increasing R & D funding	19	12	6	2	0	2	2	0	2
Private funding	6	8							
Public funding	13	4	6	2		2	2		2
Improving access to human capital	2	4	2	2	2	2	0	2	0
Human capital	2	4	2			2		2	
Inclusion				2	2				

NB: Percentages are calculated over 52 papers that addressed remedies. Numbers in parentheses indicate sectors at two-digit ISIC Revision 4 level. One paper may reference different issues within the remedy and different remedies and can address more than one sector. Only sectors that reference remedies are shown. ND, not defined.

Although not relevant to publications focused on the pharmaceutical industry, studies on most other sectors focus mainly on improving collaboration and communication (as part of R & D routines), including with customers and competitors (Belderbos et al., 2015), and on the crucial role of **public funding** (Raymond et al., 2015; Audretsch and Belitski, 2020).

1.3. Discussion

A wide variety of studies analyse RP. We grouped them into those that focus on the production of codified knowledge (scientific outputs; scientometric framework), innovations and related outcomes (innovation outputs and outcomes; innovation framework) and the impact of producing knowledge and innovations on societies (societal impact framework). Even when we focus on one of these three frameworks, the innovation framework, we find a wide variety of studies that focus on different outputs, and therefore a range of potential definitions of RP.

We categorise studies based on four definitions of RP: **innovation based** (mostly interested in innovation outcomes, not strictly measured as patents); **patent based** (mostly interested in the production of new knowledge through patents); **economics based** (mostly interested in firm level or aggregated labour or total factor productivity (TFP)); and **impact based** (mostly interested in impacts beyond labour or TFP).

The studies on innovation and patents are mainly interested in the relationship between several R & D inputs and innovation outcomes. They focus on R & D-intensive sectors (Pavitt, 1984), where the main output of the firms are innovations, such as pharmaceuticals and chemicals. The main form of innovation is therefore product innovation, with radical innovations produced more frequently than in other sectors.

Studies on economic and other impacts mainly investigate the role of R & D in firm performance, measured through TFP, sales or profits (or, more rarely, through other outcomes such as environmental sustainability and health), through innovations. They focus on any sector, such as scale intensive, specialised suppliers and R & D intensive, and investigate any form of innovation, including product, process and organisation. These can be radical innovations or (more often) incremental innovations.

Given their stronger focus on radical innovations, studies on innovation that use the patent-based definition of RP are those more concerned with a potential decline in RP. In this context, decline is seen in terms of not only patents but also new drugs, chemical components and NMEs. Studies that use the economics- and impact-based definitions of RP are concerned with R & D performance, but do not focus as much on if firms need to invest more in R & D to achieve the same impacts on TFP, value added or profits.

Despite these differences in focus, when it comes to understanding what factors may negatively affect RP, studies across the innovation-based and impact-based definitions of RP do not differ substantially in relation to the categories of factors that may hinder RP. Within those categories, though, the specific factors are likely to differ. For instance, in the innovation/patent RP literature, the focus is on processes of R & D-intensive firms, knowledge recombination, teamwork and scientists' incentives to publish. These factors are less relevant to the economics-/impact-based RP literature, which is more concerned with aspects of firm management, firm organisation and industrial policy incentives such as R & D cuts.

Such differences are also reflected in the remedies discussed in the two different groups of literature. Methods, specific processes and knowledge-related issues, such as open access, promoting diversity and reducing the relevance of research evaluation, are the main remedies for studies focused on innovation-/patents-based RP. However, they are less relevant to studies focusing on economic-/impact-based RP. Firm organisation, policy instruments and private funding are more relevant to these.

Within the two groups of literature, there is also a lot of heterogeneity, in relation to both the types of hindering factors and how they could affect RP, and the methods and their implementation. These differences are very important because combating them would require ad hoc policies, depending on the types of innovation needed, and the sector.

This heterogeneity holds even in the case of the innovation-/patent-based RP studies, where most of the research has focused on the R & D-intensive pharmaceutical industry. Within pharma (and even more if we expand to biotech), many ways of improving RP are discussed, especially in relation to processes and methods.

Differences in the details of each remedy category are even higher in the case of the economic-/impact-based RP literature, which does not focus on a specific sector, but usually studies firms across all industries (especially in manufacturing).

2. Small-scale survey

We conducted a small-scale exploratory survey among experts to collect more nuanced views on the potential decline in RP (beyond the pharma sector), the main hindering factors and remedies, and how OS practices may contribute to RP and their impact on societal outcomes. Using the definition of RP in the innovation framework ([9]), survey participants were

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([9]) This framework is based on the ratio of research inputs (e.g. funding and researchers' time) to innovative outputs (e.g. new technologies, patents, drugs and solutions to problems); improving RP requires improving the efficiency of the asked to focus their answers on tangible innovative outputs other than publications. The survey was organised into four sections.

- **Respondent profile.** Individual information that might influence the responses (e.g. disciplinary background, sector, gender and geopolitical region of expertise) was collected.
- **Research productivity and hindering factors.** Respondents' perceptions of the decline in RP, the main factors hindering RP and the main remedies to address those hindering factors were assessed.
- **Research productivity and OS.** Respondents' perceptions of the contribution of specific OS practices to RP by addressing the main hindering factors were gathered.
- **Research productivity and societal impact.** This section asked about respondents' perceptions of the relationship between RP and the societal impact of research, and the contribution of OS to improving this relationship.

Results are based on 52 responses, distributed as follows.

- Discipline:
  a) social sciences (all social sciences and humanities) – 61 %;
  b) natural sciences (agricultural science, physical sciences and engineering, and medical and health sciences) – 30 %;
  c) multidisciplinary background ('other backgrounds' and any combination of disciplines between the natural and social sciences) –9 %.
- Organisation/employment:
  a) research institutions and universities (e.g. university, research institute or think tank) – 75 %;
  b) public sector (e.g. government or military forces) – 15 %;
  c) private sector (e.g. business enterprise or self-employed) – 4 %;
  d) non-governmental organisation (NGO) – 4 %;
  e) other – 2 %.
- Gender:
  a) male – 67 %;
  b) female – 31 %;
  c) prefer not to say – 2 %.
- Geopolitical region of expertise ([10]):
  a) Europe – 54 %;
  b) Latin America – 30 %;
  c) Asia – 21 %;
  d) North America – 17 %;
  e) Africa – 12 %;
  f) Oceania – 4 %;
  g) no region – 25 %.

2.1. *Perception of research productivity decline*

research system or funding in generating/developing innovations, which may lead to socioeconomic benefits.

([10]) The sum of the shares is larger than 100 because several respondents declared expertise in several regions.

In the survey, participants were asked to express their opinion on **whether or not RP has declined** in their field and if **the number and/or value of breakthroughs has declined in the past 10 years**.

With regard to the first question, we found that the majority of respondents did not think that there had been a general decline in RP in the 10 years before the survey. A total of 30 respondents (58 %) believed that RP had increased, 9 (17 %) considered that it had remained stable, 5 (10 %) did not know if it had changed and only 8 (15 %) said that it had declined (Table 12).

Table 12. Overall perception of increase or decline of RP

Response	Frequency	Percentage
Increased	30	58
Stable	9	17
Declined	8	15
Do not know	5	10
Total	**52**	**100**

The distribution of responses by disciplinary background (Table 13) shows that the perception of an increase in RP is similar across disciplines. The main difference is in perception of decline: a bigger share of respondents with a social sciences background agreed that RP had declined (13 %), while only 1 respondent from the natural sciences (2 %) and none of the respondents with a multidisciplinary background considered this to be the case.

The perception of an increase in RP is also similar across sectors of employment (relatively speaking). Only respondents working for research institutions and universities (15 %) considered that there had been a decline in RP (13 % from the social sciences and 2 % from the natural sciences). The perception of an increase in RP is also maintained across different regions of expertise (Table 14), but experts on Europe are relatively more evenly distributed between perceptions of RP increasing, remaining stable and declining than experts in other regions, who more often perceived an increase in RP.

Table 13. Percentage of respondents perceiving an increase or decline in RP by discipline and sector (%)

Discipline					
	Increased	Stable	Declined	Do not know	Total
Social sciences	33	9	1	6	61
Natural sciences	17	8	2	2	29
Multidisciplinary	8	0	0	2	10
Total	58	17	15	10	100
Sector					
	Increased	Stable	Declined	Do not know	Total
Research institutions and universities	40	12	15	8	75
Public sector	10	5	0	0	15
Private sector	8	0	0	2	10
Total	58	17	15	10	100

Table 14. Percentage of respondents perceiving an increase or decline in RP by region of expertise (%)

Response	Europe	Latin America	Asia	North America	Africa	Oceania	No region
Increased	25	21	13	10	8	4	15
Stable	15	4	4	2	2	0	4
Declined	10	4	2	2	2	0	4
Do not know	4	0	2	2	0	0	2

These results are in stark contrast with the evidence presented by Bloom et al. (2020), who conclude that there has been a general decline in RP. They also differ from our literature review (Table 6), where we found that around 32 % of the reviewed papers referred to a decline in RP, and only 5 % to an increase. Therefore, there is some disagreement between the literature, mainly focused on pharma and other research-intensive sectors, and the perception of researchers from different disciplinary backgrounds, sectors of employment and regions of expertise on the decline in RP. This requires further exploration.

With regard to breakthroughs (research outputs with major impacts on society), approximately 31 % of the respondents considered that the number and/or value of breakthroughs had remained stable (Table 15). A similar percentage (27 %) answered that the number of breakthroughs and/or their value have increased, while 23 % considered that they have declined. There is, therefore, a less clear pattern with regard to breakthroughs. However, there is a disciplinary difference in the perception of breakthrough decline (Table 16). Respondents with a social sciences background were slightly more inclined to perceive a decline

(19 %) than an increase (15 %) or stability (15 %). Respondents with a natural sciences background were more likely to perceive an increase (12 %) or stability (10 %) than a decline (2 %), and those with a multidisciplinary background mainly perceived stability (6 %) rather than a decline (2 %) or an increase (0 %). In terms of sector of employment, respondents from research institutions and universities tended to perceive a stable production of breakthroughs (27 %), although a good share of respondents also perceived a decline (19 %) and an increase (15 %). In contrast, respondents from the public and private sectors tended to perceive an increase (8 % and 4 %, respectively) rather than a decline (4 % for public and 0 % for private) or a stable production of breakthroughs (2 % each). Perceptions of decline also vary by region of expertise (Table 17). For instance, respondents with expertise in Europe are similarly distributed between perceptions of an increase (12 %), stability (15 %) and a decline (12 %), while respondents with expertise in Latin America seemed to be more likely to perceive an increase (12 %) than a decline (6 %) or a stable pattern (8 %).

Table 15. Overall perception of decline or increase in breakthroughs

Response	Frequency	Percentage
Stable	16	31
Increased	14	27
Declined	12	23
Do not know	10	19
Total	52	100

Table 16. Percentage of respondents perceiving a decline or an increase in breakthroughs by discipline and sector (%)

Discipline					
	Stable	Increased	Declined	Do not know	Total
Social sciences	15	15	19	12	61
Natural sciences	10	12	2	5	29
Multidisciplinary	6	0	2	2	10
Total	31	27	23	19	100
Sector					
	Stable	Increased	Declined	Do not know	Total
Research institutions and universities	27	15	19	13	75
Public sector	2	8	4	2	15
Private sector	2	4	0	4	10
Total	31	27	23	19	100

Table 17. Percentage of respondents perceiving a decline or an increase in breakthroughs by region of expertise (%)

Response	Europe	Latin America	Asia	North America	Africa	Oceania	No region
Stable	15	8	6	6	2	2	8
Increased	12	12	6	2	0	0	8
Declined	12	6	8	6	6	0	8
Do not know	15	4	2	2	4	2	2

In summary, on average respondents claimed that RP had increased in the 10 years before the survey and that the number or quality of breakthroughs had remained constant. This may suggest that, although researchers perceive that the number of research outputs per input has increased, they consider that the 'value' of those outputs has not. However, this observation does not hold across disciplines, sectors and regions of expertise in relation to breakthrough productivity. For instance, respondents with a social sciences background were more likely to perceive a decline in breakthrough productivity than respondents with a natural sciences background. The fact that some researchers in the field of physics considered that there had been an increase in breakthroughs may point to developments that the literature on RP did not capture because of their recency. In any case, these differences merit further research.

2.2. The relationship between research productivity and the societal impact of research

Respondents overwhelmingly thought that increasing RP could lead to a greater societal impact ([11]): 56 % answered that the extent to which increasing RP contributes to societal impact was either large (29 %) or very large (27 %), while 23 % considered the contribution moderate. Only 3 respondents (6 %) said that increasing RP did not contribute to a greater societal impact, and 5 (10 %) answered that RP contributes only to a small (8 %) or a very small extent (2 %) to societal impact (Table 18) ([12]).

Table 18. Societal impact of RP

Response	Frequency	Percentage
Does not contribute	3	6
To a very small extent	1	2
To a small extent	4	7
To a moderate extent	12	23

([11]) This was defined as 'the contribution of research to societal challenges (e.g. economic growth, more and better jobs, health, sustainable agriculture, food security, climate action) or the sustainable development goals (e.g. zero hunger, gender equality, reduced inequalities, clean water and sanitation)'.

([12]) A total of 3 (6 %) respondents did not know if RP contributes to societal impact.

To a large extent	15	29
To a very large extent	14	27
Do not know	3	6
Total	52	100

Overall, the view that '[m]ost research[ers] indulge their own interest[s] and focus on things unlikely to have strong social impact' seems to be rare among the respondents. However, even those who think that increasing RP contributes to a greater societal impact often qualify their reply. For example, they state that 'it seems self-evident that greater rates of innovation will generate solutions of importance'; 'more research in relevant areas will uncover new materials/processes/devices, etc. that can help meet societal challenges if it is possible for their potential to be realised (commercialisation or general uptake, i.e. use of the information is the hindering step, not generation of the research results)'; 'The more sound research is produced and made available to a vast audience (including lay people) the higher the chances that it's translated into policies and triggers behavioral change'; and 'Societal impact of research should become more important and since basic research, aiming for scientific breakthroughs, and applied research aiming for societal impact require different attitudes, focus on research productivity is important to create societal impact'.

The respondents who believe that increasing RP contributes to societal impact to a moderate extent are even more conditional in assessing the way in which RP may contribute to societal outcomes. Their explanations include: 'It is only a small portion of the research enterprise that focuses on societal impacts – we need to build more robust support and a larger community of researchers that engage in this type of research'; 'Relevant knowledge can have societal impact, but is by itself not sufficient for that'; and 'We need quality (public value) research, not merely more research (made by researchers jockeying for personal advance)'.

Although none of those who said that RP does not contribute to a greater societal impact are from the social sciences and humanities, all those who answered that it only contributes to a small or very small extent are from the social sciences and humanities.

Table 19. Societal impact of RP perceived by participants by disciplinary background (%)

Response	Multidisciplinary	Natural sciences	Social sciences	Total
Does not contribute	2	4	0	6
To a very small extent	0	0	2	2
To a small extent	0	0	8	8
To a moderate extent	0	8	15	23
To a large extent	2	8	19	29
To a very large extent	4	9	13	27
Do not know	2	0	4	6
Total	10	29	61	100

These respondents mentioned that 'societal impact does not depend mainly on research productivity' but on 'actions toward producing change toward a given social relevant objective'.

We did not detect significant differences across disciplines (Table 19) or genders.

With regard to region of expertise we noticed first that respondents with expertise in Asian countries and those with no specific regional expertise were more likely to believe that RP has only a moderate impact on societal outcomes than those with expertise in other regions. These respondents raised concerns such as 'because in LDCs no one takes research seriously not it results, government plays a key role in [the] implementation of research policy' and 'We need quality (public value) research, not merely more research (made by researchers jockeying for personal advance)'.

Second, respondents with expertise in Latin American countries were more likely to believe that RP has a very large impact on societal outcomes. One respondent explained that this was '[b]ecause the achievement of the Agenda 2030's SDGs implies innovative solutions and a systemic approach. This demands the higher research productivity as possible.' Another commented that '[r]esearch leads to innovation and better understand of society contributing to a more civilized, sustainable, equal and prosperous way of living'. However, this group of respondents warned that RP can have a large impact on societal outcomes only '[a]s far as research funding and research assessment is oriented to social problems and social engagement'. The requirement for engagement was stressed by another respondent: 'The more sound research is produced and made available to a vast audience (including lay people) the higher the chances that it's translated into policies and triggers behavioral change.'

Third, respondents with expertise in African countries were indifferent among all options (Table 20).

Table 20. Societal impact of RP perceived by participants by region of expertise (%)

Response		Europe	Latin America	Asia	Africa	Oceania	North America	No region
Does not contribute		2	2	2	2	2	2	4
To a very small extent		2	0	0	0	0	0	0
To a small extent		2	0	2	2	0	2	0
To a moderate extent		13	8	10	2	0	2	10
To a large extent		17	6	4	2	0	6	6
To a very large extent		13	12	2	2	2	4	4
Do not know		4	2	2	2	0	2	2

When we compare participants' perceptions of the impact of RP on societal outcomes and their perceptions of a decline in RP, we do not find a significant relationship, except that all those who answered that RP had not changed in the 10 years before the survey answered that RP has at least a moderate effect on societal outcomes (Table 21)

Table 21. Societal impact of RP perceived by participants by perception of RP decline (%)

Response	Declined	Stable	Increased	Do not know	Total
Does not contribute	0	0	6	0	6
To a very small extent	0	0	2	0	2
To a small extent	2	0	4	2	8
To a moderate extent	2	8	12	2	23

To a large extent	8	6	13	2	29
To a very large extent	2	4	19	2	27
Do not know	2	0	2	2	6

Respondents from the private sector said that RP does not contribute to the societal impact of research (Table 22). This may indicate that they have a different understanding of RP, societal impact and/or the role of science in society. Indeed, one of the two respondents distinguished the two dynamics, commenting that 'This question is not precise enough. You can have a high research productivity in a sector or done in a way that will not have a strong societal impact. It is not about productivity but about how and why the research is done.' On the other hand, both respondents from NGOs believed that RP has a large societal impact. However, both of them warned that this is the case only for research that is oriented towards social problems: 'It seems self-evident that greater rates of innovation will generate solutions of importance as long as the focal areas of research are relevant to society' or, in other words, RP can have a large impact '[a]s far as research funding and research assessment is oriented to social problems and social engagement'.

Table 22. Societal impact of RP perceived by participants by organisation (%)

Response	NGO	Other	Private	Public	Research	Total
Does not contribute	0	0	4	0	2	6
To a very small extent	0	0	0	0	2	2
To a small extent	0	0	0	0	8	8
To a moderate extent	0	0	0	8	15	23
To a large extent	2	0	0	2	25	29
To a very large extent	2	2	0	6	17	27
Do not know	0	0	0	0	6	6

2.3. Factors hindering research productivity and potential remedies

The respondents identified evaluation pressure or incentives (46 %) and R & D management (38 %) as the two main factors hindering RP (Table 23). Issues raised in relation to evaluation pressure included (i) a disproportionate focus on number of publications as an indicator of productivity, (ii) a reliance on bibliometric impact factors for evaluation, (iii) evaluation criteria for funding that suppress interdisciplinarity, (iv) potential flaws in the peer review system and (v) the pressure by national evaluation systems such as the Research Excellence Framework in the United Kingdom that may 'push … academics' to conduct "research that may not be applicable or needed, to satisfy [the] REF [Research Excellence Framework]'.

In relation to R & D management, respondents focused mainly on (i) the heavy administrative burden that prevents researchers from focusing on their main work; (ii) managerial criteria that impose strict guidelines that do not align with research needs, which also reduces time for research; and (iii) the lack of flexibility in academic careers to reward entrepreneurial skills and achievements 'rather than being forced to pay the more traditional research and or teaching tracks for career advancement'.

The third main factor indicated by the respondents was cost (29 %). Respondents mainly pointed out (i) a lack of funding for longer-term projects; and (ii) the uneven distribution of funds towards specific disciplines (such as social sciences) or towards specific aims such as innovation and social impact. The fourth factor was regulation (19 %). Besides the reasons related to evaluation discussed previously, respondents pointed out the need to establish research priorities for funding, for instance through mission-oriented policies. The fifth factor was human capital (12 %). This was mainly related to obstacles to accessing highly skilled researchers due to the precariousness of research contracts and lack of time owing to other activities such as teaching.

To a lesser extent, respondents also pointed out issues of managing collaborations (10 %), siloed knowledge (10 %) and path dependence (10 %). Regarding collaboration, they identified a lack or inefficiency of triple helix collaboration, network formation and teamwork. In relation to siloed knowledge, respondents described a lack of openness to knowledge sharing that may be further incentivised by academic institutions and IPR policies. In relation to path dependence, they state that 'institutions are biased towards conventional ideas' and that funding agencies are 'risk averse', which does not provide an adequate environment to pursue 'new ideas'.

The relative importance of the hindering factors provided by the respondents is quite similar to that found in the literature, with two relevant exceptions: (i) fewer mentions of market pressure; and (ii) a much stronger emphasis by the respondents on evaluation pressure and R & D management issues than in the literature. This is likely to be due to a bias in the survey responses: respondents are more likely to consider their personal situation, rather than more general evidence (as would be the case in a published study). Table 23 offers a comparison of the hindering factors from the literature review and the survey.

Table 23. Comparison between hindering factors from the literature review and the survey

Hindering factors	Share of papers (%) (*)	Share of survey respondents (%) (**)
R & D routines	50	46
Firm management	20	2
R & D process	18	0
R & D management	9	38
Closed science	2	8
R & D incentives	48	63
Regulation	23	19
IPR	14	8
Evaluation pressure	11	46
Fast-expanding endless frontier	45	42
Knowledge frontier	23	4
Human capital	11	12
Costs	11	29
Knowledge combination	32	27
Siloed knowledge	16	10
Managing collaborations	9	10
Disciplinarity	5	4
Path dependence	2	10
Market pressures	23	6
Capitalism pressure	16	6
Competition	7	0

NB: Some totals may differ from the sum of categories because one respondent/paper can reference more than one category.
(*) Shares of papers are calculated over 44 papers that contributed hindering factors.
(**) Shares of respondents are calculated over 52 respondents with valid responses.

Alongside the main hindering factors, the main remedies identified by respondents emphasised the need to change research evaluation systems to foster RP (38 %), increase public funding (25 %), create policy instruments (25 %), improve firm management (21 %) and provide open access (19 %).

In relation to addressing hindering factors related to evaluation pressure, respondents made several proposals. These include assessing novelty instead of number of publications and other outputs; creating incentives for performing non-standard types of research, such as research conducted with patients in medicine; rewarding collaboration, interdisciplinarity and quality; and using evaluation to learn and improve and not only to rank academics and institutions. Some respondents also argued for more stable research career paths. One respondent suggested that it should be easier to dismiss unproductive academics.

With regard to increasing public funding, respondents identified a general need for more funding for high-risk research projects not attached to any mission, longer-term funding, simplifying calls for funding, and prioritising areas of research with stronger social relevance. Mission-oriented funding was suggested as one option, noting that research-funding systems need to find ways to incentivise high-risk research and novel ideas. Along these lines, policy instruments identified by respondents include incentives for collaboration between academia, industry and governments, less focus on bibliographical outputs as a criterion for awarding funds, identifying key areas where breakthroughs are needed and improving research policy planning. Specifically for research institutions and universities, changing the criteria for hiring and tenure was identified by one respondent as needed to encourage interdisciplinary research.

Regarding firm management, researchers noted a need to provide more recognition of research as part of the central activities of the firm, for instance by awarding prizes and other incentives. Such incentives could include offering longer-term contracts, reducing bureaucracy and administration burden in universities, providing better access to knowledge resources such as patents, and changes in the structure and roles of firm staff.

In relation to open access, respondents identified a need for new publication media such as working paper databases to make research publicly available and developing new open access databases, reducing ‘dependence on big publishing houses’, providing researchers with the opportunity to choose the most appropriate licenses for their work and promoting OS partnerships.

To a lesser extent respondents also pointed out potential remedies to increase RP that were coded under R & D management (13 %), collaboration (13 %) and human capital (13 %). On R & D management, the respondents proposed specific changes, such as more flexible use of funds, reduced complexity of funding processes, and giving researchers a leading role on the whole research process instead of managers. On collaboration, respondents call for better networking mechanisms to ‘improve teamwork’. On human capital, they suggested improving recruitment practices by providing more flexible ‘tenure and hiring decisions criteria’, mentoring and training new researchers, providing a ‘stimulus for new scientists establish a career in research’ and longer-term contracts. They also identified the need to ‘eliminate gender bias against females in academia’.

Considering the main categories for remedies (in bold in Table 24), the literature and the survey responses coincide in focusing on improving R & D routines. The categories within R & D routines preserve a relatively similar share between the literature and the survey responses. However, new methods, technologies and OS – except for open access – were not mentioned by the respondents.

There is an agreement between the literature and the survey respondents also with regard to improving governance, improving management and organisation, and increasing R & D funding. However, several differences emerged in the distribution of responses coded within these three general categories. These were research evaluation (probably their own), firm management, public funding and policy instruments. Respondents did not identify remedies related to market strategies, incremental innovation and specialisation, strategies that may be more relevant to entrepreneurs and managers than to researchers. Table 24 compares the literature with the survey responses.

Table 24. Comparison between remedies from the literature review and the survey

Remedy	Share of papers (%) (*)	Share of survey respondents (%) (**)
Improving R & D routines	83	50
R & D management	23	13
New methods	15	0
R & D process	12	4
Collaboration	10	13
Open access	8	19
Technologies	6	0
R & D organisation	4	8
Interdisciplinarity	4	2

Remedy	Share of papers (%) (*)	Share of survey respondents (%) (**)
OS	2	0
Improving governance	27	35
Regulation	12	10
Policy instruments	12	25
IPR protection	4	4
Improving management and organisation	27	23
Firm organisation	13	2
Firm management	8	21
Market strategies	6	0
Setting strategies for R & D priorities	25	56
Paradigm shift	6	10
Social impact orientation	4	4
Incremental innovation	4	0
Specialisation	4	0
Diversification	4	8
Research evaluation	4	38
Increasing R & D funding	25	25
Private funding	13	0
Public funding	12	25
Improving access to human capital	15	15
Human capital	12	13
Inclusion	4	2

NB: Some totals may differ from the sum of categories because one respondent/paper can reference more than one category.

(*) Shares for papers are calculated over 52 papers that contributed remedies.

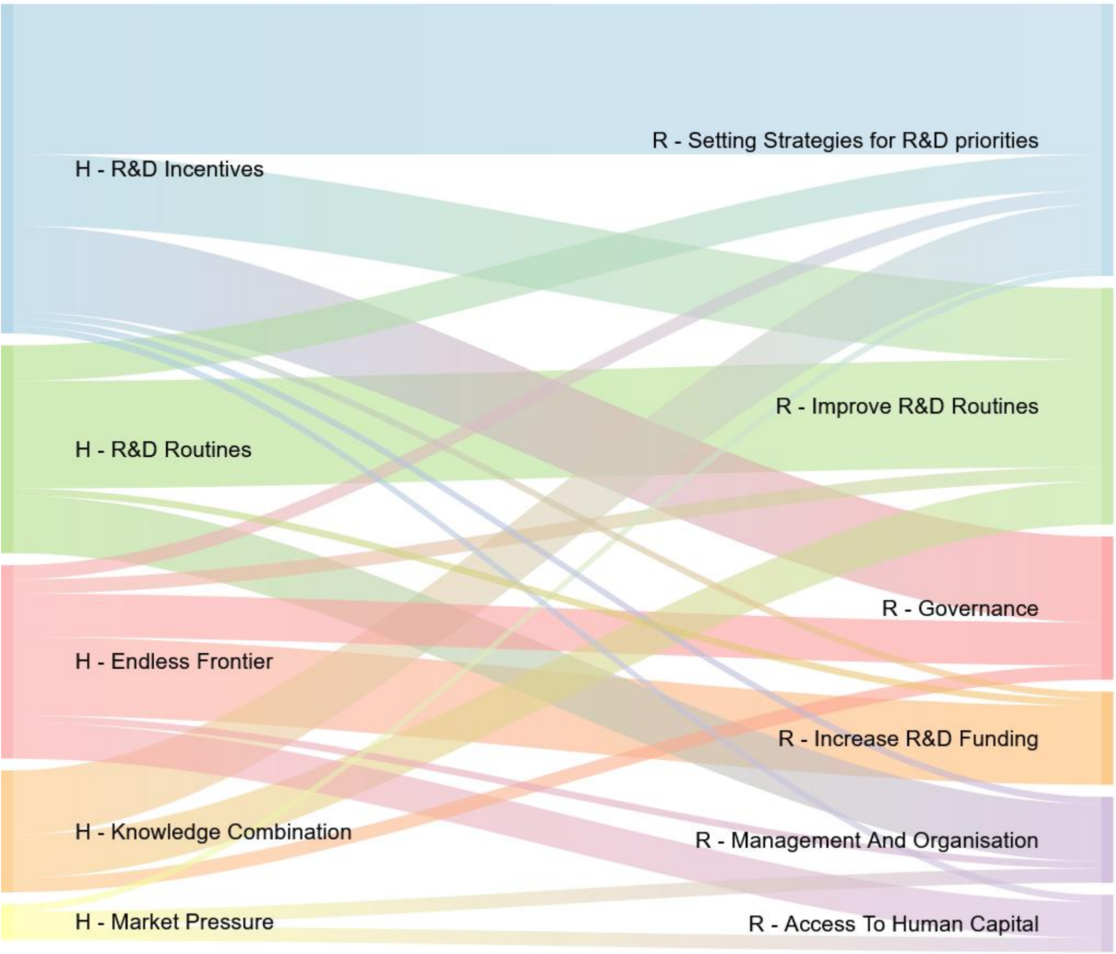
(**) Shares of respondents are calculated over 52 respondents.

In Figure 11 we present a Sankey diagram that connects hindering factors and remedies based on the survey responses. The figure confirms the strong relationship between hindering factors related to R & D incentives and setting strategies for R & D priorities as a main remedy, specifically a

change in research evaluation systems. This connection was less relevant in the literature (Figure 10), which tended to instead prioritise an improvement in R & D routines as the main remedy for inefficient R & D incentives (also mentioned by some survey respondents).
There was also a strong connection between inefficient R & D routines as hindering factors, and potential ways of improving R & D routines through suggestions discussed earlier in this section. As in the literature, changes in R & D priorities and in R & D management were also considered relevant to addressing inefficient R & D routines by survey respondents.

Finally, remedies to cope with the fast-expanding endless frontier are like those pointed out by Bloom et al. (2020), specifically improving access to human capital, increasing funding and improving governance. This is somewhat different from what we found in the literature, where the connection was instead stronger with remedies related to improving R & D routines and setting strategies for R & D priorities.

Figure 11. Sankey diagram of hindering factors and remedies from the survey



NB: The size of the categories is given by the number of relationships, rather than by the number of papers.

In analysing the survey, we noted that there were some hindering factors and remedies that did not fit the categories we built from the literature. These were exogenous variables, such as the COVID-19 pandemic, structural social organisation issues such as reliance on physical personal interactions, and discrimination against women and potentially other vulnerable groups in academia. Although these issues were pointed out only by three respondents, we consider them potential avenues of research to better understand RP.

2.3.1. The role of open science in research productivity

In the OS section of the survey, we listed nine OS practices organised in three groups: **open access and sharing research outputs**, which includes four OS practices related to open access to publication, FAIR data principles, open licences, and documenting and sharing workflows and methods openly; **research collaboration**, which includes three OS practices related to interdisciplinarity, networked science / crowdsourcing science and transdisciplinarity / citizen science; and **engaging and translating**, which includes two OS practices related to communicating science to society. Each of the nine OS practices were properly defined in the questionnaires, as shown in Table 25. We first asked respondents to assess if each of the OS practices in Table 25 could contribute to increasing RP, and if this was because they address any of the two hindering factors that respondents indicated as the most important in reducing RP.

Table 25. OS practices included in the survey questionnaire and their definitions

	OS practice	Definition
Open access and sharing of research outputs		
	Open access to scientific publications	Principles and practices that enable the distribution of research publications free of cost and other barriers to readers, through any model (green, gold, hybrid, diamond, etc.)
	Operationalisation of FAIR data principles	Findable, accessible, interoperable and reusable: https://www.force11.org/fairprinciples
	Open licences	Intellectual property mechanisms that allow the reuse of research outputs. For example, creative commons licenses.
	Documenting and sharing workflows and methods openly	Practices for documenting research processes, for example GitLab or open notebooks such as LabTrove
Research collaboration		

	OS practice	Definition
	Interdisciplinarity	Interdisciplinary research involves research processes that integrate methods and practices from two or more disciplines or bodies of specialised knowledge
	Networked science and crowdsourcing science	Research projects characterised by a wide base of potential contributors that share their research inputs and outputs openly in digital infrastructures. Contributors may be involved in particular tasks of the research cycle.
	Transdisciplinary research and citizen science	Projects that involve collaboration with communities/citizens at different stages of scientific processes and/or that integrate knowledge from scientific disciplines and non-academic communities.
Engaging and translating		
	Public communication of science	Engaging with mass and social media to disseminate research outputs such as newspapers articles, briefings, blog posts, podcasts and social network posts.
	Interactive activities to include society in scientific discussions	Interaction activities responding to social concerns or interests that contribute to the social valorisation of science such as science clubs, science shops and science observatories.

Respondents were positive about the role of OS practices in contributing to RP. Most of them (96 %) identified at least one OS practice as potentially relevant to increasing RP (Table 26). Most respondents indicated that open research collaboration practices (92 %) and open access practices (90 %) were relevant to RP; while a lower (but still high) proportion of respondents considered relevant engaging and translating practices (65 %) relevant to RP. In particular, interdisciplinarity was identified as relevant by the most respondents (79 %), followed by operationalising FAIR data principles (75 %), and documenting and sharing workflows and methods openly (75 %).

There were some differences in the disciplinary backgrounds of respondents, as shown in Table 27. Open access and research collaboration practices were considered relevant to almost all scholars in natural sciences (93 % and 100 %, respectively), while only 60 % of them claimed that engaging and translating was important for RP. In terms of specific open access practices, FAIR data principles (Figure 17 in Annex 5) and open licences (Figure 18 in Annex 5) and documenting and sharing workflows and methods openly (Figure 19 in Annex 5) were identified as relevant to these disciplinary backgrounds. Interestingly, regarding research collaboration practices, all respondents from natural sciences claimed that interdisciplinarity contributed to RP (Figure 20 in Annex 5). Most of them also valued transdisciplinarity (Figure 22 in Annex 5). For social scientists, although a higher proportion of scholars also considered open access and research collaboration (88 %) as important for RP than those who considered engaging and translating (69 %), the difference in proportions between these groups was lower than for natural scientists. So in relative terms, social scientists valued the latter practices more than natural scientists.

Following insights from the literature review, and the discussion with experts involved in the pilot, the survey also included a more critical question to assess whether or not OS practices could hinder RP. The majority (63 %) of respondents believed that this is not the case. When asked to identify OS practices that may hinder RP, some respondents mentioned open licences (12 %), operationalising FAIR data principles (12 %) and interdisciplinarity (12 %) (Table 26).

Table 26. Percentage of respondents stating that OS practices could contribute to or hinder RP (%)

	Respondents stating that OS may contribute to RP	Respondents stating that OS may hinder RP
Open access	90	25
Open access publications	60	4
FAIR data principles	75	12
Open licences	60	12
Documenting and sharing	75	8
Open collaboration	92	27
Interdisciplinarity	79	12
Networked science	65	6
Transdisciplinarity	56	10
Engagement options	65	15
Communication	45	10
Interaction with society	61	6
Any OS practice	96	37

Table 27. Percentage of respondents stating that OS practices could contribute to RP, by discipline (%)

Discipline	Open access and sharing of research outputs	Research collaboration	Engaging and translating	Any OS practice
Multidisciplinary backgrounds	100	100	60	100
Natural sciences	93	100	60	100
Social sciences	88	88	69	94
OS practices by type contributing to productivity	90	92	65	96

2.3.2. The role of open science practices in addressing hindering factors

In the questionnaire, respondents who stated that OS may contribute to increasing RP were asked to identify whether OS could address any of the two main hindering factors they had identified in their earlier answers. Respondents also had the option to indicate that OS practices could address other hindering factors, not identified by them.

The majority of respondents (83 %) associated at least one OS practice with the two hindering factors that they identified. In this section we comment on the contribution of OS practices to the four most commonly mentioned categories of hindering factors: the fast-expanding endless frontier, knowledge combination, R & D incentives and R & D routines. In summary, OS practices contribute significantly to the fast-expanding endless frontier, knowledge combination and R & D incentives but not so much to R & D routines. Open collaboration and open access practices contribute more to alleviating those hindering factors than engagement.

Table 28 shows the contribution of OS practices to addressing the factors hindering RP identified by the respondents. The most frequent contributions are related to **research collaboration practices**: 86 % of respondents identifying hindering factors in the fast-expanding endless frontier category believed that at least one of these research collaboration practices help in addressing them. Similarly, 90 % of respondents who mentioned hindering factors in the knowledge combination and R & D incentives categories and 67 % of those identifying hindering factors in the R & D routines category stated that research collaboration practices could help. In order of importance, 82 % of respondents who identified hindering factors in the fast-expanding endless frontier category; 90 % of respondents mentioning knowledge combination factors; 79 % of respondents identifying R & D incentive factors; and 63 % of respondents mentioning R & D routines factors believed that open access and sharing of research output practices could contribute to addressing factors hindering RP. In turn, practices related to **interaction with society** were seen as contributing less than other practices. Some 64 % of respondents identifying hindering factors in the fast-expanding endless frontier category, and a lower proportion of respondents identifying factors in the other categories, stated that these practices could contribute to addressing hindering factors.

In more detail, as most factors in the **fast-expanding endless frontier** category are related to the cost of research, some OS practices, especially networked science, the public communication of science and interdisciplinarity (see Table 28) were thought to contribute to reducing these costs. For example, respondents suggested that sharing paves the 'way for new research and stimulates innovation' and that 'academics can meet other research more easily and create academic networks'.

With regard to factors in the **knowledge combination** category, respondents suggested that operationalising FAIR data principles, networked science and interdisciplinary (see Table 28) could improve the management of collaborations and connect otherwise siloed knowledge. Respondents also suggested that the availability of open data and results meant that they could be used in innovative ways. They also mentioned that open collaboration practices provide opportunities to apply knowledge to new contexts and to new problems, which may lead to new, fruitful interpretations by scholars from different disciplines.

Finally, in relation to the most frequently mentioned hindering factors in the **R & D incentives** category (e.g. narrow bibliometric evaluation practices), respondents indicated that some OS practices (especially documenting and sharing workflows and methods openly, interdisciplinarity and networked science (see Table 28)) may reduce evaluation pressure by enabling more open discussions – less structured within disciplinary borders guiding evaluation schemes – of different ideas in science and by increasing 'visibility and ability to identify new collaborators and areas for joined activities, new insights and especially for poor countries the ability to build on existing research (if this research is closed they cannot afford access)'.

Table 28. Percentage of respondents identifying OS practices that contribute to addressing hindering factors (%)

	Fast-expanding endless frontier	Knowledge combination	R & D incentives	R & D routines
Any open access practice	82	90	79	63
Open access publications	23	30	33	13
FAIR data principles	14	60	33	21
Open licences	18	50	28	21
Documenting and sharing	32	40	36	17
Any open collaboration practice	86	90	90	67
Interdisciplinarity	36	40	44	21
Networked science	45	50	38	25
Transdisciplinarity	27	40	28	13
Any engagement practice	64	50	56	42
Communication	41	20	21	8
Interaction with society	36	20	28	25
Any OS practice	86	90	90	67

NB: Percentage is the respondents who answered that OS practices contribute to each hindering factor as a proportion of the total responses identifying that hindering factor.

In an open question, the survey asked respondents to provide examples of how OS practices improved RP in their field. Some 63 % of respondents provided responses. Some of these examples are listed below; they relate to the potential of OS to improve research efficiency, to increase research quality and problem-solving capacity, or to create visibility and awareness of relevant issues.

Increasing research efficiency

- 'Open data facilitates research and lowers the cost of collecting data.'
- 'Sharing raw data used in research leads to new science.'
- '[A]ccess to more information allows me to do more research.'
- 'Sharing of data means less duplication in data production' and 'allow[s] access to other's work so it doesn't have to be repeated'
- 'More data [is] available and there [is] less need for reproducing experiments.'

- 'Implementing digital STI [science, technology and innovation] practices promote the sharing of real time data analysis and processing methods, including access to research data, raw files, code lines, etc.'
- 'They enable [the] reuse of knowledge more quickly by a more diverse set of actors poised to put it in use quickly.'

Increasing research quality and problem solving

- 'When data and results are available to all – then there is more opportunity for others to utilize these resources in innovative ways which really can develop and lead to breakthroughs. Walking around a challenge and being able to view it through other disciplinary eyes is key to seeing new ways of solving challenges.'
- 'Opening to different players increased the relevance of the research question and how to frame research, which in the end increased the productivity of scientists.'
- 'Facilitate replication *and* facilitate doing things differently.'
- 'Open science and making data available to the general public will contribute to [the] integrity of scientists.'
- 'Access to open databases allows for increase of robustness of research results.'
- 'Research question[s] emerging from societal needs may directly contribute to address[ing] current and future societal challenges.'
- 'Open research data and open infrastructures can contribute with the reproducibility of research in other regions and contexts.'
- 'One of the drivers to obtain a fast vaccine for COVID-19 was open data reservoirs.'

Creating awareness and improving communication

- 'Contribute to wider awareness and [our] understanding of data and methods, including new advances; help [to] ensure that more researchers are aware of and engaged with cutting edge advances'
- 'Peer-review of papers often takes years in the top journals of my field. OS practices permit scientists to communicate results before peer-review, which reduces the barriers to open discussion of ideas in science.'
- 'Openly sharing research results leads to increased visibility and ability to identify new collaborators and area of joined activities, new insights and especially for poor countries the ability to build on existing research (if this research is closed they cannot afford access).'
- 'Citizen science will create more awareness on the relevance and impact of science and will create a larger work force for science.'

2.3.3. What might constrain the adoption of open science practices?

In another open question, we asked respondents to identify the main constraints to adopting OS practices. Some 69 % answered this question. They referred to constraints related to:

- the costs of implementing OS practices, which may shift funds from research itself, as these budget lines are usually not recognised separately by funders (e.g.

to pay the extra costs of documenting and sharing workflows and methods openly);

- evaluation schemes and less tangible issues related to reputation, mentality and research culture that favour competition over collaboration;
- journals with article-processing charges that are too expensive;
- lack of technical and institutional support and training on how to implement OS;
- lack of technical infrastructure that could guarantee, for example, data security.

2.3.4. The role of open science in translating research productivity into societal impact

The last section of the survey requested respondents to indicate on a Likert scale (0–5) the extent to which OS practices may contribute to increasing the societal impact of research. There was large consensus that they could: 90 % of respondents answered that at least one OS practice could contribute to a 'large' or 'very large extent' to increasing the societal impact of research (Table 29). In general, the higher expectations were on **interdisciplinarity**: 67 % of respondents answered that this practice could contribute to the societal impact of research to a large or very large extent. This was followed by **FAIR data principles** (58 %) and **communication of science** (58 %).

Table 29. Percentage of responding stating that OS practices could contribute to a large or very large extent to the societal impact of research (%)

Type of OS practice	Societal impact
Any open access practice	71
Open access publications	52
FAIR data principles	58
Open licences	40
Documenting and sharing	54
Any open collaboration practice	77
Interdisciplinarity	67
Networked science	46
Transdisciplinarity	46
Any engagement practice	60

Communication	58
Interaction with society	46
Any OS practice	90

There were some differences across disciplinary backgrounds (see Table 30). Respondents from natural sciences were particularly optimistic about **research collaboration** practices: in particular, they valued interdisciplinarity (see Figure 29). In addition, respondents from these disciplines were the most optimistic about some of the OS practices related to **open access and sharing of research outputs**, particularly regarding the potential contribution of open licences (Figure 27 in Annex 5, possibly influenced by the COVID-19 crisis) and documenting and sharing workflows and methods openly (Figure 28 in Annex 5). In contrast, less than 50 % of respondents in natural sciences considered the potential of engaging and translating practices as highly relevant, while 63 % of researchers from social sciences did.

Table 30. Percentage of responding stating that different types of OS practices could contribute to a large or very large extent to the societal impact of research, organised by discipline (%)

Disciplines	Open access and sharing of research outputs	Research collaboration	Engaging and translating	Any OS practice
Multidisciplinary backgrounds	60	80	80	80
Natural sciences	80	87	47	93
Social sciences	69	72	63	91
Total OS practices by type with a large impact	71	77	60	90

2.4. Discussion

The survey focused on two main lines of inquiry.

1) Do experts perceive a decline in RP, and what might be the main hindering factors and the main remedies to address them?
2) How might specific OS practices address some of the factors hindering RP? Can OS practices help in translating RP to societal impact?

Regarding question 1, we found that the majority of respondents did not think that there was a decline in RP in the 10 years before the survey. The perception of a decline in RP was even lower than was found in the literature review. This was an intriguing finding that we aimed to explore in our final workshop (see Section 3.2).

Respondents identified evaluation pressure / incentives (63 %) and R & D routines (46 %) as the two main factors hindering RP. Issues raised in relation to evaluation pressure included a disproportionate focus on a ‘publish or perish’ culture, overreliance on impact factors for evaluation and flaws in peer review systems. With regard to R & D management, respondents considered that there is a heavy administrative burden that impedes researchers from focusing on their main work, and managerial incentives that may drive research efforts away from high-risk research.

As for remedies to address those and other factors hindering RP, one relevant finding is that specific remedies depend on the research area or sector. However, some of the main overarching remedies identified relate to changes in research evaluation systems (e.g. assessing novelty instead of number of publications), more stable career paths for young researchers, more public funding (e.g. chances of winning grants are too small for the effort invested in applying for them), and several improvements in R & D management and firm management, depending on context.

As for question 2, the combination of different OS practices and disciplinary backgrounds of the respondents produced a wide variety of potential functions that OS may have in addressing the main factors hindering RP. A number of results stand out. Almost all respondents (96 %) endorse the role of OS practices in contributing to RP. In particular, interdisciplinarity was identified by the most respondents (79 %) as relevant to the practices they were assessing, followed by operationalising FAIR data principles (75 %), and documenting and sharing workflows and methods openly (75 %). In particular, OS practices related to more open research collaboration and open access and sharing research outputs seemed to alleviate hindering factors related to managing collaborations, evaluation pressure and the cost of research. In our open questions, respondents suggested that OS may improve RP by improving the efficiency of conducting research (e.g. by avoiding duplication, increasing the use of existing knowledge stocks and collective intelligence) and research quality and reliability (e.g. owing to increased transparency and reproducibility).

Respondents also strongly endorsed the role of OS practices in increasing the impact of RP on society, especially through increasing interdisciplinary research. Respondents also provided some practical suggestions on how OS practices may improve the impact of RP on society. The suggestions included the contribution of OS to increasing the alignment of research priorities with societal needs (e.g. diversity and plurality in scientific participation could improve problem identification, and increased trust and visibility may promote dialogue with research users).

3. Discussion

3.1. Summary of the research

For more than half a century, scholars (from Machlup (1962) to Bloom et al. (2020)) have recurrently pointed out that investments in R & D have decreasing returns: in order to attain a similar number of innovative outputs and improvements in economic and social conditions, research funding needs to increase. This is because the stock of knowledge increases and moves in several directions, which require more and more research inputs (Mokyr, 2005). In addition, emerging recombinations of knowledge require researchers to expand their domain or to become very specialised, leading to stronger path dependence (Chu and Evans, 2021) and higher transaction costs (Williamson, 1981).

A systematic review of the literature has shown that scholars have investigated this phenomenon of declining RP only in a few sectors, particularly those related to science-based industries such as pharmaceuticals and biotech. The literature investigating the number of innovations per research input is heterogeneous, uses very different methods and does not provide strong causal evidence to identify the factors that hinder or increase RP. Less than half of the studies reviewed mention the decline in RP as a problem.

However, the literature discusses, and at times examines, a rather vast array of hindering factors. We grouped them into **five categories**: inefficient R & D routines; market pressures that drive innovation away from social welfare; R & D incentives that do not promote high-risk research; the fast-expanding endless frontier of new knowledge needed for innovations; and difficulties in combining different areas of knowledge.

Studies also provide options for addressing these and other hindering factors. We grouped them into **six categories**: improving R & D routines, improving the governance of R & D; improving the management and organisation of R & D; setting strategies for R & D priorities; increasing R & D funding; and improving access to human capital.

The specific hindering factors differ depending on the focus of the literature. For instance, in the innovation-based RP literature, the focus is on processes of R & D-intensive firms, knowledge recombination, teamwork and scientists' incentives to publish. These factors are less relevant to the economic RP literature, which is more concerned with aspects of firm management, firm organisation and industrial policy incentives such as R & D cuts.

Such differences are also reflected in the remedies discussed. Methods, specific processes and knowledge-related issues, such as open access, promoting diversity and reducing the relevance of research evaluation, are the main remedies for studies focused on innovation-based RP literature. However, they are less relevant for studies focusing on economics-based RP literature. Studies in this area of literature focus more on firm organisation, policy instruments and private funding.

While only 32 % of the reviewed papers mention a decline in RP, the perception of this decline is even less frequent among researchers and practitioners (who have studied the topic or who make R & D funding decisions). Only 8 out of the 52 experts (15 %) that took part in our survey noticed a decline in RP. This very low percentage may also be due to participants perceiving RP as the number, rather than the value, of outputs (indeed, academic outputs have increased). This was confirmed by a further discussion with experts (Annex 6)

Besides the decline, most of our respondents provided two major factors that may hinder RP and two remedies to address them. The hindering factors were not very different from those studied in the literature. Remedies, instead, were more focused on evaluation pressure, and the need to provide more freedom to researchers and to reduce their administrative burden. These are remedies that affect individual productivity but not necessarily the production of innovations at societal level (for instance, collaborations were rarely mentioned in the survey, despite having been the focus of attention of many studies in the literature reviewed). Once more, the difference here may be due to the cognitive process of an expert that responds to their individual opinion, versus a study that investigates the problem from the perspective of the literature.

As the literature retrieved in our systematic review did not analyse the role of OS practices, we explicitly asked the survey respondents if OS can help to improve RP. We also explicitly asked if OS could address the main factors hindering RP that they indicated. Their responses were very useful in sketching different ways in which OS practices may improve RP. Almost all respondents endorsed the role of OS practices in contributing to RP (96 %). Interdisciplinarity was identified as relevant by the most respondents (79 %), followed by operationalising FAIR data principles (75 %), and documenting and sharing workflows and methods openly (75 %). OS practices related to more open research collaboration and open access and sharing research outputs seemed to alleviate hindering factors related to managing collaborations, evaluation pressure and the cost of research.

Respondents also strongly endorsed the role of OS practices in increasing the impact of RP on society, especially through greater interdisciplinarity. Several respondents mentioned arguments related to the contribution of OS in making research priorities better aligned with and more responsive to societal needs (e.g. diversity and plurality in scientific participation could improve problem identification, and increased trust and visibility may promote dialogue with research users).

Although these findings suggest a number of specific ways to increase RP, in our further discussion with experts they noted that although OS practices may make research more efficient, they come at an administrative cost that has to be borne by researchers (Annex 6), who in the survey indicated that they already have too strong an administrative burden. This may call for nuanced policies that address such trade-offs between different incentives.

3.2. Policy recommendations

As noted in the discussion with experts in the workshop, it may be problematic to focus policies to improve RP on the definition of productivity based only on the innovation framework, that is the ratio between research inputs (e.g. funding and human capital) and innovation outputs (e.g. technologies, ideas, breakthroughs and solutions to problems) ([13]). Although this definition is broader in terms of outputs and potential economic and societal impacts than the definition of RP in the scientometric framework ([14]), it is still too narrow to measure the impact that research inputs may have on broader societal outcomes, over different time frames. This may lead to incentives for all actors in the research system to invest in a lower than optimal number of, less radical, innovation outputs. This is because innovation is nurtured by failure, but failures in innovation reduce efficiency. It also does not adequately consider how positive and negative impacts of innovation inputs and outputs are distributed across society, and thus is biased towards scientific, technological and economic impacts, and against societal impacts ([15]).

Combining evidence from the literature, the survey and the discussion with experts during the workshop, we put forward the following five complementary policy recommendations.

([13]) Improving RP requires improving the efficiency of the research system or funding in generating/developing innovations, which may lead to socioeconomic benefits.

([14]) The ratio of research inputs (e.g. funding and human capital) to knowledge codified in bibliographical outputs (publications and patents).

([15]) https://ec.europa.eu/info/research-and-innovation/strategy/support-policy-making/shaping-eu-research-and-innovation-policy/evaluation-impact-assessment-and-monitoring/horizon-europe_en

3.2.1. Efficiency: increasing R & D funding may be necessary, but it is not sufficient

In Section 1.2.4, we showed that the increasing cost and diminishing returns of R & D was identified by the literature as an important factor hindering RP (what we call the 'fast-expanding endless frontier'). Increasing costs, a lack of funding for long-term, high-risk projects, the uneven distribution of funding across disciplines, the orientation of research (basic versus applied), and novelty (radical versus incremental) were key factors identified by the survey respondents (Section 2.3).

Both the literature and the survey respondents identified the need to increase funding to expand the knowledge frontier and maintain RP. This remedy is considered less frequently than actions that address the following main hindering factors (Sections 1.2.4 and 2.3): existing R & D incentives that promote incremental, low-risk and short-term research, with uncertain impacts on societal well-being (due to current regulations, market and non-market evaluations of research, and the extreme specialisation of research), and inefficient R & D routines and processes (due to regulations and the slow uptake of innovative tools and methods).

As also pointed out by the experts (Annex 6), the issue of funding highlights more complex problems of prioritisation, human capital and regulation that cannot be addressed only by increasing resources. For R & D to be more productive in generating innovations that may lead to socioeconomic benefits, the following actions are needed.

- Facilitate the development of human capital and access to talents that break existing socioeconomic barriers, as this is the creative input that transforms funding into knowledge and innovations, and a key component of potentially achieving impact. Current barriers to including large strata of the society in the innovation process reduce the innovative capacity of economies (Saha and Ciarli, 2018; Akcigit et al., 2020) and reduce the impact of innovations on large parts of society that may benefit most (Cheng and Weinberg, 2021; Koning et al., 2021).
- Better plan and design research funding, including processes to define priorities (discussed in the next recommendation), interacting with research users to strengthen the links between research and society, and promoting useful failures of R & D projects.
- Promote the diffusion of organisational and technical innovations that improve the efficiency of R & D routines.
- Promote and facilitate collaboration between researchers, and across organisations, disciplines and sectors, funding the time needed for those collaborations to become productive by breaking epistemic boundaries.
- Explore and understand the effects of different incentives and policies in motivating researchers to look beyond and expand the knowledge frontier, using experiments and investing in evaluations (NESTA, 2021).

3.2.2. Changes in research funding priorities: balancing relevance to societal challenges, diversity and failures

As we will show in Section 3.3, only a small share of R & D is related to major societal challenges such as the SDGs, for instance when research targets innovations in new molecular entities used in drugs, or new seeds that may have better yields in less productive land (e.g. see sectors addressed in Tables 9 and 11 in Section 1.2.4). In addition, even when this is the case, the relevance of this R & D to societal challenges is not granted (see Annex 6). Pharmaceutical research frequently targets diseases that are not very relevant to the large share of the population that lives in low- and lower-middle-income countries (Yegros-Yegros et al., 2020) and agricultural research may not be aligned with the societal needs of the countries in which it is conducted (Ciarli and Ràfols, 2019).

Changes in the design of research funding policies towards societal challenges (e.g. climate change, deep social inequalities, violent conflicts and the health problems of the most marginalised) may help to steer innovations/ideas in directions that are most relevant to society, and increase RP, beyond research efficiency – that is, considering societal outcomes rather than successful innovation as the output. However, a focus on grand challenges should be complementary to an expansion, rather than a reduction, in the space for researchers to explore ideas with low probability of success, but potentially high impact and novelty. This includes undertaking inter- and transdisciplinary research and pursuing radically different avenues for research (which may produce fewer successful innovations than expected by current measures of success).

3.2.3. Changes in research evaluation practices and in the measurement of research productivity: combining efficiency and societal impact

Neither of the two previous recommendations is likely to work under the current incentive system designed by market and non-market regulations and evaluation practices. Evaluation pressure has been identified by surveyed researchers as the main factor hindering RP (see Table 23 in Section 2.3), and most of the reviewed studies also identify R & D incentives as the main hindering factor (Table 8). Evaluations based exclusively on bibliometric quantitative assessments and market pressures that privilege high returns on innovation investments provide a strong incentive to focus on incremental changes rather than more radical breakthroughs. Evaluation schemes were also mentioned as a barrier to adopting OS practices (Section 2.4.2).

Although evaluation pressure is more likely to be felt by researchers in academia than in sectors closer to the market such as pharma or high-tech ICT (Annex 6 and Table 9 in Section 1.2.4), studies on these sectors singled out market pressures and evaluations based on the number of products or innovations as factors hindering productivity. For example, in the pharmaceutical industry scientists feel the pressure to produce new molecular entities leading to short-term economic benefit, which has created a research environment in which scientists feel displaced by managers and shareholders.

Whether it is pressure to publish, pressure to produce a commercial innovation, or another form of pressure, there is a need to understand how funding and assessment should be designed and organised with a focus on increasing RP and generating a greater societal impact.

How evaluation systems should be revised is beyond the objectives of this report, but the following are options that could be explored in further research, based on the discussion in the workshop, the literature review, the survey and our own expertise on the subject.

- One size does not fit all. Research evaluation systems should be adapted to the purpose of the evaluators or the policy programmes that support the research (Reed et al., 2021). For instance, if the aim is to produce radical innovations, assessments should consider the high likelihood of failure and replace indicators of bibliographical production with indicators of, for example, learning and improvement along different technological trajectories.
- Evaluating for learning is an important process. Many evaluations are communicated but their recommendations are not discussed or implemented. This leads to stagnation and saturation, as the same recommendations keep coming up in different evaluations. For this reason, a learning system is needed so that both the policy programme and the researchers can build collective capacity and reflect on evaluation for both the design and the execution of the funding of R & D projects.
- While evaluations based on bibliometrics are a useful complement, guidelines and recommendations that explain good practices, such as the Leiden Manifesto (Hicks et al., 2015) and the Declaration on Research Assessment (DORA) (ASCB, 2012), should be used. For instance, because traditional bibliometrics mainly address reputation and recognition, rather than novelty, risk or societal transformation, and rely on closed access journals, there is room to build new indicators and ways to analyse research outputs that value innovation and social impact.

1.1.1. Open Science policies: open science practices may increase research productivity, but they need adequate support

OS may improve RP at a systemic level owing to its effects on research efficiency (avoiding duplication, increasing the use of knowledge stocks and collective intelligence); research reliability (owing to increased transparency and reproducibility); and research responsiveness to social needs (diversity and plurality in scientific participation could improve problem identification and increased trust and visibility may promote policy dialogue).

OS includes a variety of practices and infrastructures – **access and sharing research outputs**, **research collaboration**, and **engaging and translating** – that are not discussed by the literature on RP (Section 1.2.4). Increased awareness and research on the opportunities and problems of OS in relation to RP is needed.

Despite the perceived benefit for RP (Section 2.4), respondents identified a number of obstacles to OS adoption, which can be addressed by public policies.

- Evaluation schemes should incorporate a wider set of outputs, including open data, and practices such as creating networks, engaging with society, and communicating and translating research outputs for a wider audience.
- Transdisciplinary and interdisciplinary collaborations take more time. Therefore, the evaluation process should accommodate longer deadlines, and perhaps lower scientific production, during the stages in which scientists need to better learn to collaborate across epistemic communities.
- *Current evaluation systems prioritise competition over collaboration. As collaboration is costly, regulations should provide more incentives for collaborating and sharing. For example, this can be done by making open data mandatory after an embargo period and, as we discuss below, by providing the support for researchers to be able to do so.*
- The current model of open access, based on article-processing charges, denies many institutions the opportunity to expand their research and increases the existing hierarchies in scientific communication. This suggests the need for a renewed model for scientific communication guaranteeing maximum communication between the producers and consumers of knowledge at minimum cost.
- There is a perceived lack of infrastructure that needs to be identified to support initiatives such as open collaboration and shared infrastructures. For example, interoperability across repositories is key to open data; institutional support for digital solutions for the automation of data validation and personal data protection is required to facilitate data sharing.
- Institutional support is required to develop and implement harmonised open data policies, including the creation of institutional spaces for learning technologies and metadata protocols.

OS practices can be administratively costly, for researchers and organisations. However, as the social benefits of OS are considered greater than the individual costs, there is a need to address this market failure by facilitating open access practices in organisations, for example through administrative support and facilitating access to research data infrastructures, and as discussed previously to consider them in the evaluation of research projects (Annex 6).

Other undesirable effects of OS may require policy interventions. OS may lead to less variety in research trajectories, for example if the availability of data reduces the incentives to search for data from different sources. This could lead to a reduction in exploration (Annex 6). To balance the short-term gains of reduced costs and the long-term cost of reduced exploration, in a world in which data are shared, funding programmes should consider funding projects that have very similar objectives and data, even if in the short term this may be seen as a duplication of resources.

3.2.4. Systemic changes in the value chain of research and development practices

For the above policies to be successful, it is necessary to foster coordination among funders, researchers and research users to change research practices, priorities and evaluation systems. Taken alone, the recommendations may not have an impact on RP, or the contribution of research to societal well-being (Annex 6).

Prevailing funding, research and evaluation practices may not support a research culture directed at creating social value. Rather, they may prioritise the production of knowledge that increases the efficiency of organisations or individual researchers. Understanding RP from the innovation and social impact perspectives (rather than from a pure efficiency perspective) (see Section 1.1.4) requires revising these models, including documenting and creating new funding mechanisms and supporting academic practices that promote high-risk and 'unproductive' research. These include increasing the evaluation of the successful publications of failures, holding open deliberations about which areas should be prioritised, and including the research beneficiaries in such decisions.

A revised education model to attract talent pursuing careers in research is also needed. At the governance level, there is a need to implement strong collaboration mechanisms between research institutions and non-academic stakeholders (research users). This coordination requires the training of individuals and the provision of spaces and mechanisms for fruitful interactions.

As part of this systemic change, there is also a need to move away from a definition of productivity that solely considers the ratio of research inputs to innovative outputs (as used in this report) ([16]) towards a definition within the societal impact framework (see Section 1.1.4) ([17]). This requires major efforts in defining new data and indicators to capture long-term outcomes, acknowledging the value of failures, and attributing these outcomes to the collaborative outputs of research. Adopting a societal impact definition of productivity at policy level also requires building infrastructures and management strategies to adequately support interdisciplinarity, transdisciplinarity, high-risk research and OS, key issues that were identified in this study and that merit further research.

([16]) Research productivity is studied as the ratio of research inputs (e.g. funding and human capital) to innovation outputs (e.g. technologies, patents and ideas).

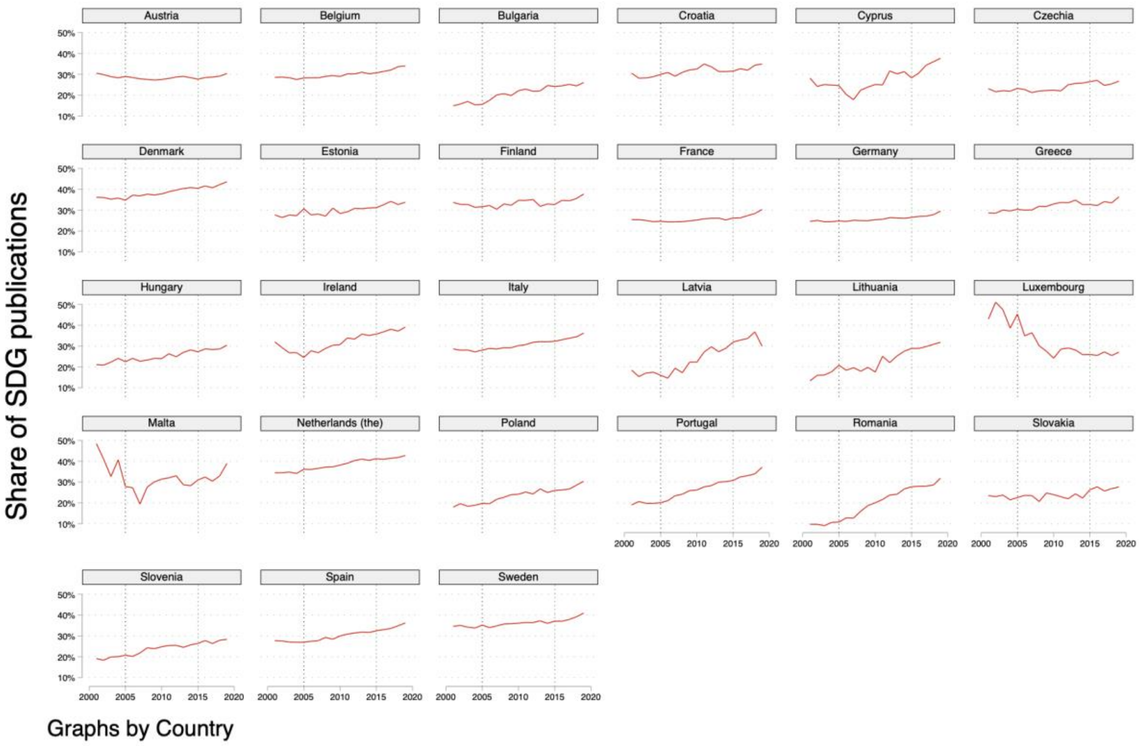
([17]) Research productivity is studied as the relationship between research inputs, how they are organised and prioritised, and their effects on society.

3.3. Further research: Thinking about productivity in terms of societal impact

To give an example of alternative ways of considering RP in relation to societal challenges, we use an indicator of the contribution of research conducted in European countries to addressing the SDGs. We used data collected and analysed in the STRINGS project, and relate the publications of researchers in the 27 European countries to one or more of SDGs 1–16 (e.g. Ciarli et al., 2021; Confraria et al., 2021; Rafols et al., 2021). For more details on the method, see Confraria et al. (2021).

Figure 12 shows that, on average across European countries, as of 2019 only 37 % of the papers published by EU researchers, and included in the Web of Science, are related to any of the first 16 SDGs. This percentage is higher now than it was in 2000, as it has increased in most countries, especially since the Millennium Development Goals (2005).

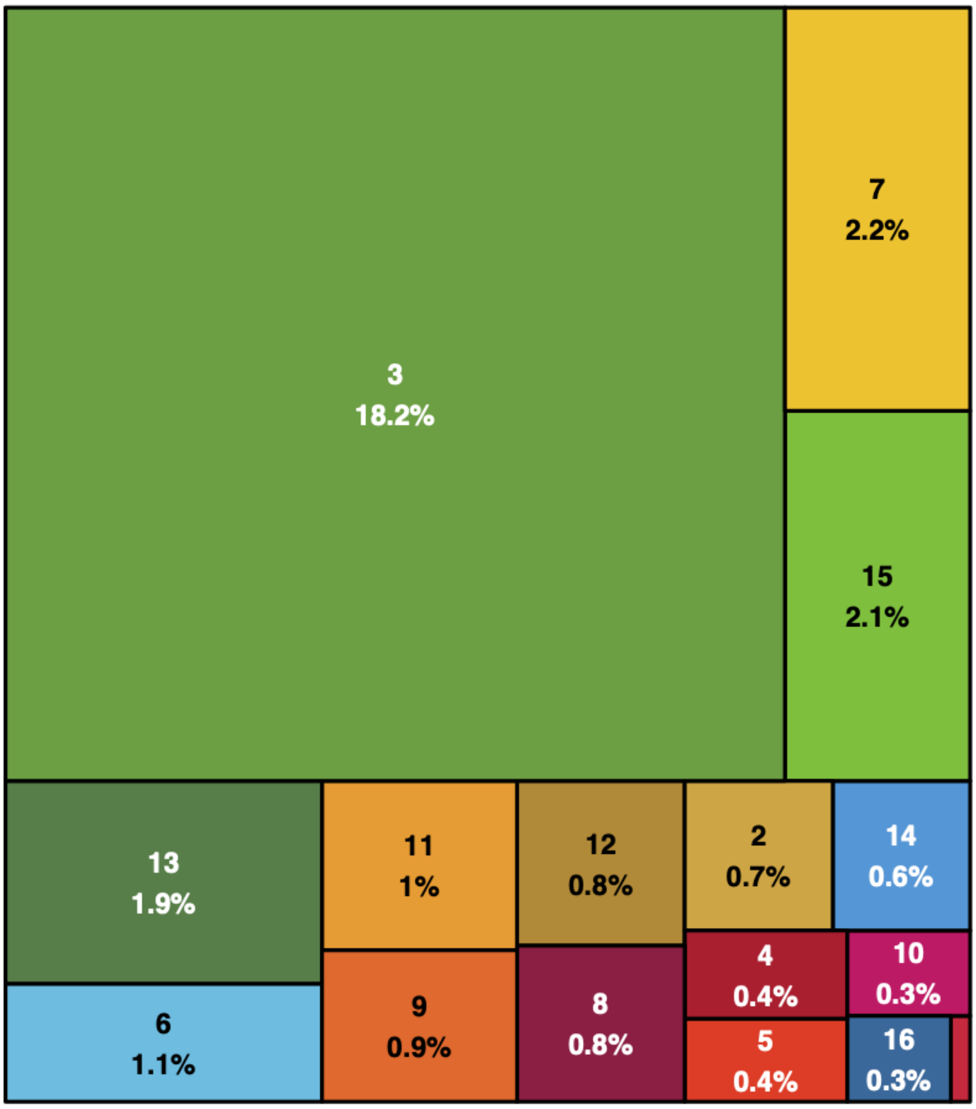
Figure 12. Percentage of SDG-related publications (in the Web of Science) in each EU country



This suggests that, overall, an increased share of research has focused more on problems that are globally defined as relevant to sustainable development. Whether this has translated into more and better outputs for sustainable development is not clear, although there is evidence that the use of SDG-related research has increased significantly in policy, in the news and on social media, and is more collaborative, open and multidisciplinary (STRINGS report, 2021).

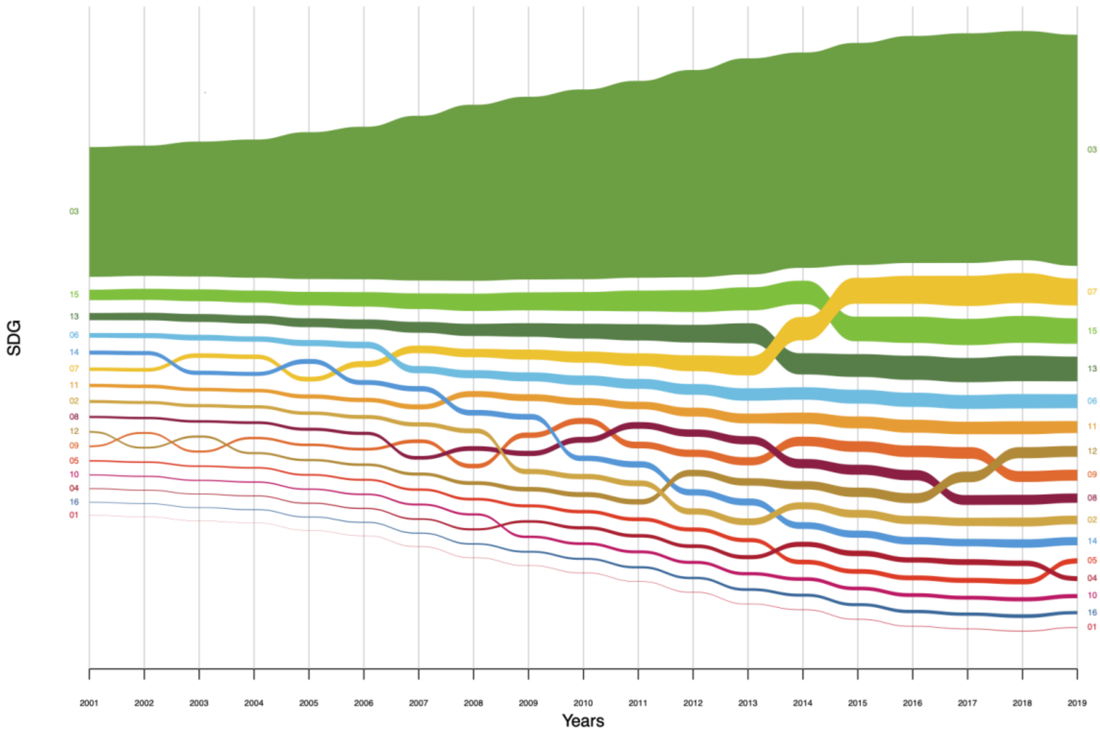
However, the distribution of SDG-related research in the EU (as in most of the rest of the world) is strongly focused on a single SDG (Figure 13). If we exclude SDG 3 (good health and well-being), the share of SDG-related research in the EU falls to around 20 %.

Figure 13. Share of SDG-related publications by SDG (EU average over 2015–2019)



The strong focus on SDG 3 has not changed substantially over the years (Figure 14), suggesting that although publications related to most SDGs have increased, the strongest contributor to SDG-related research in the EU is the expansion of health research (including pharma). As we noticed, this research includes the sectors where most papers have explored a decline in RP. Notable exceptions are the research related to SDG 7 (affordable and clean energy) and SDG 12 (responsible production and consumption), linked to finding pathways to the green transition.

Figure 14. Share of SDG-related publications by SDG between 2001 and 2019 (EU average)

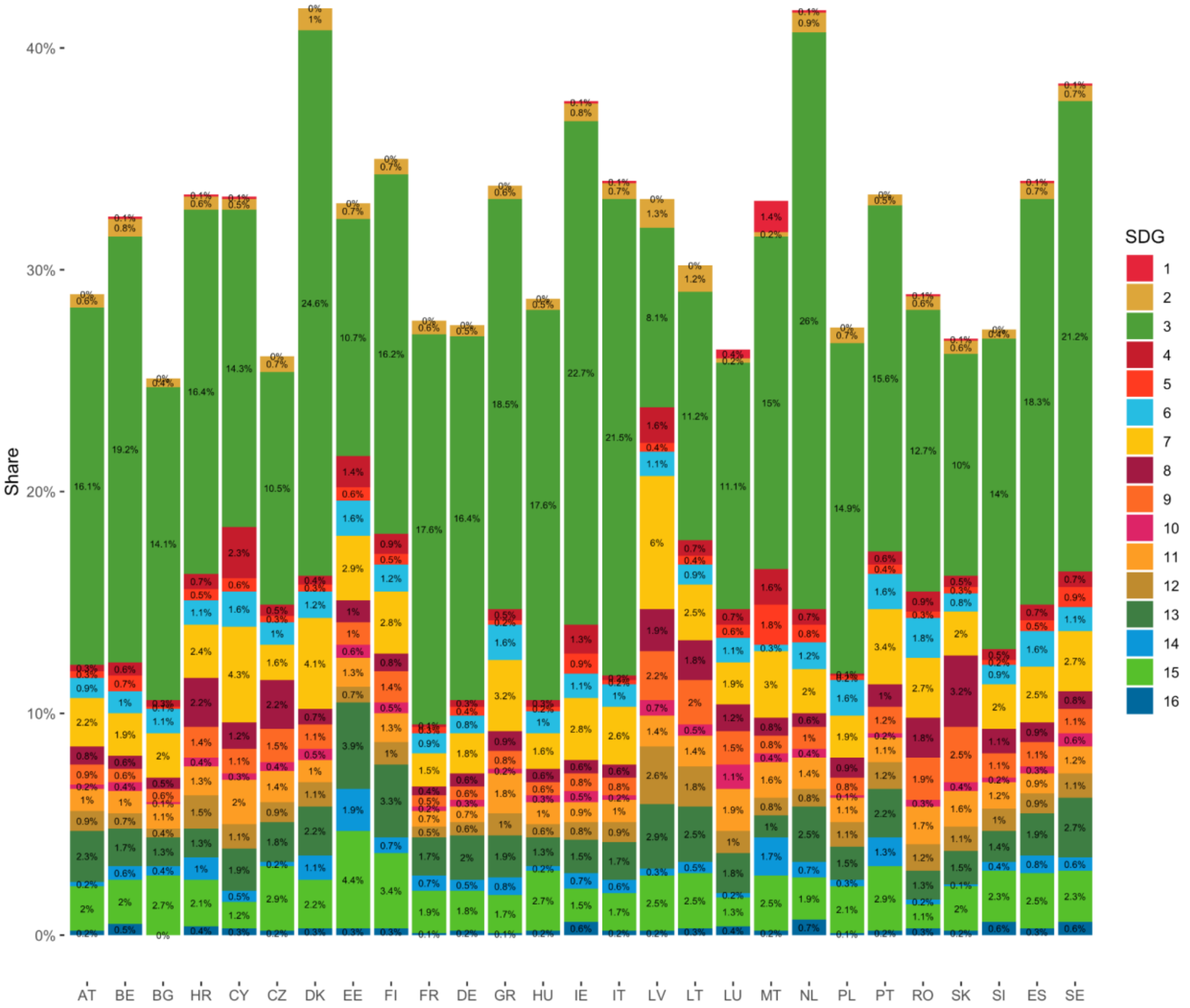


The EU average of course hides substantial differences between countries (Figure 15). First, there are substantial differences between countries in their share of SDG-related publications. Not surprisingly, Nordic countries such as Denmark, the Netherlands and Sweden seem to have a research profile that makes a stronger attempt to address issues related to sustainable development. Large countries, such as France and Germany, that contribute to a large share of EU research are instead worryingly less focused on the SDGs. Second, countries' research profiles in relation to each SDG differ substantially. For instance, the Baltic states and Finland seem to focus their research on SDGs beyond SDG 3, towards energy and the environment.

Overall, though, it is not clear the extent to which the EU research agenda, and that of its members, are focused on their SDG-related priorities (Confraria et al., 2021). There is a lot of work to be done to better understand areas in which EU countries can increase their RP, in ways that also have a stronger positive impact on societies ([18]).

([18]) See, for instance, the data and dashboard shared by SIRIS on the SDG features of Horizon projects (http://science4sdgs.sirisacademic.com/).

Figure 15. Share of SDG-related publications by SDG and EU country (2015–2019 average) (%)



4. References

Abramo, G. and D'Angelo, C. A. (2014), 'How do you define and measure research productivity?', *Scientometrics*, Vol. 101, No 2, pp. 1129–1144.

Acemoglu, D., Dorn, D., Hanson, G. H. and Price, B. (2014), 'Return of the Solow paradox? IT, productivity, and employment in US manufacturing', *American Economic Review*, Vol. 104, No 5, pp. 394–399.

Akcigit, U., Pearce, J. G. and Prato, M. (2020), 'Tapping into talent: coupling education and innovation policies for economic growth', *NBER Working Papers*, No 27862, September 2020, National Bureau of Economic Research, Cambridge, MA, doi:10.3386/w27862.

Aldieri, L., Barra, C., Paolo Vinci, C. and Zotti, R. (2021), 'The joint impact of different types of innovation on firm's productivity: evidence from Italy', *Economics of Innovation and New Technology*, Vol. 30, No 2, pp. 151–182, doi:10.1080/10438599.2019.1685211.

Arthur, W. B. (2009), *The Nature of Technology: What it is and how it evolves*, Simon and Schuster, New York.

ASCB (American Society for Cell Biology) (2012), 'San Francisco declaration on research assessment', DORA (https://sfdora.org/read/).

Audretsch, D. B. and Belitski, M. (2020), 'The role of R & D and knowledge spillovers in innovation and productivity', *European Economic Review*, Vol. 123, doi:10.1016/j.euroecorev.2020.103391.

Baba, Y., Shichijo, N. and Sedita, S. R. (2009), 'How do collaborations with universities affect firms' innovative performance? The role of "Pasteur scientists" in the advanced materials field', *Research Policy*, Vol. 38, No 5, pp. 756–764, doi:10.1016/j.respol.2009.01.006.

Belderbos, R., Carree, M. and Lokshin, B. (2006), 'Complementarity in R & D cooperation strategies', *Review of Industrial Organization*, Vol. 28, No 4, pp. 401–426, doi:10.1007/s11151-006-9102-z.

Belderbos, R., Carree, M., Lokshin, B. and Fernández Sastre, J. (2015), 'Inter-temporal patterns of R & D collaboration and innovative performance', *Journal of Technology Transfer*, Vol. 40, No 1, pp. 123–137, doi:10.1007/s10961-014-9332-4.

Bhattacharya, J. and Packalen, M. (2020), 'Stagnation and scientific incentives', *NBER Working Papers*, No 26752, February 2020, National Bureau of Economic Research, Cambridge, MA.

Bloom, N., Jones, C. I., van Reenen, J. and Webb, M. (2020), 'Are ideas getting harder to find?', *American Economic Review*, Vol. 110, No 4, pp. 1104–1144, doi:10.1257/aer.20180338.

Bowen, A. and Casadevall, A. (2015), 'Increasing disparities between resource inputs and outcomes, as measured by certain health deliverables, in biomedical research', *Proceedings of the National Academy of Sciences of the United States of America*, Vol. 112, No 36, pp. 11335–11340, doi:10.1073/pnas.1504955112.

Bruder, S., Hackenschmidt, S., Moldenhauer, E. J. and Kabisch, J. (2018), 'Conventional and oleaginous yeasts as platforms for lipid modification and production', in Bornscheuer, U. T. (ed.), *Lipid Modification by Enzyme and Engineered Microbes*, Academic Press and AOCS Press, Urbana, IL, pp. 257–292, doi:10.1016/C2016-0-04104-9.

Brynjolfsson, E., Rock, D. and Syverson, C. (2019), 'Artificial intelligence and the modern productivity paradox: a clash of expectations and statistics', in Agrawal, A., Gans, J. and Goldfarb, A. (eds), *The Economics of Artificial Intelligence: An agenda*, University of Chicago Press, Chicago, IL, pp. 23–60.

Burgelman, J.-C., Pascu, C., Szkuta, K., Von Schomberg, R., Karalopoulos, A., Repanas, K. and Schouppe, M. (2019), 'Open science, open data, and open scholarship: European policies to make science fit for the twenty-first century', *Frontiers in Big Data*, Vol. 2, No 43, doi:10.3389/fdata.2019.00043.

Bush, V. (1945), *Science, the Endless Frontier*, National Science Foundation, Washington DC.

Capone, F., Lazzeretti, L. and Innocenti, N. (2021), 'Innovation and diversity: the role of knowledge networks in the inventive capacity of cities', *Small Business Economics*, Vol. 56, No 2, pp. 773–788, doi:10.1007/s11187-019-00268-0.

Caputo, M., Lamberti, E., Cammarano, A. and Michelino, F. (2016), 'Exploring the impact of open innovation on firm performances', *Management Decision*, Vol. 54, No 7, pp. 1788–1812, doi:10.1108/MD-02-2015-0052.

Cheng, W. and Weinberg, B. A. (2021), 'Marginalized and overlooked? Minoritized groups and the adoption of new scientific ideas', *NBER Working Papers*, No 29179, August 2021, National Bureau of Economic Research, Cambridge, MA, doi:10.3386/W29179.

Chu, J. S. G. and Evans, J. A. (2021), 'Slowed canonical progress in large fields of science', *Proceedings of the National Academy of Sciences*, Vol. 118, No 41, e2021636118, doi:10.1073/PNAS.2021636118.

Ciarli, T., Confraria, H., Rafols, I., Chataway, J. and Stirling, A. (2021), 'Research priorities may not align with the SDGs: policy suggestions to steer them', in IATT (United Nations Interagency Task Team on Science, Technology and Innovation for the Sustainable Development Goals) (ed.), *Emerging Science, Frontier Technologies, and the SDGs – Perspectives from the UN system and science and technology communities*, IATT, New York, pp. 90–98.

Ciarli, T. and Ràfols, I. (2019), 'The relation between research priorities and societal demands: the case of rice', *Research Policy*, Vol. 48, No 4, pp. 949–967, doi:10.1016/j.respol.2018.10.027.

Cobb, J. N., Juma, R. U., Biswas, P. S., Arbelaez, J. D., Rutkoski, J., Atlin, G., Hagen, T., Quinn, M. and Ng, E. H. (2019), 'Enhancing the rate of genetic gain in public-sector plant breeding programs: lessons from the breeder's equation', *Theoretical and Applied Genetics*, Vol. 132, No 3, pp. 627–645, doi:10.1007/s00122-019-03317-0.

Cockburn, I. M. (2004), 'The changing structure of the pharmaceutical industry', *Health Affairs*, Vol. 23, No 1, pp. 10–22, doi:10.1377/hlthaff.23.1.10.

Confraria, H., Ciarli, T. and Noyons, E. C M. (2021), 'Countries' research priorities in relation to the sustainable development goals', 18th International Conference of the International Society for Scientometrics and Informetrics, Leuven, 12–15 July 2021.

Crafts, N. (2018), 'The productivity slowdown: is it the "new normal"?', *Oxford Review of Economic Policy*, Vol. 34, No 3, pp. 443–460.

Cuatrecasas, P. (2006), 'Drug discovery in jeopardy', *Journal of Clinical Investigation*, Vol. 116, No 11, pp. 2837–2842, doi:10.1172/JCI29999.

Cummings, T. and Knott, A. M. (2018), 'Outside CEOs and innovation', *Strategic Management Journal*, Vol. 39, No 8, pp. 2095–2119, doi:10.1002/smj.2792.

Du, J.-L., Liu, Y. and Diao, W.-X. (2019), 'Assessing regional differences in green innovation efficiency of industrial enterprises in China', *International Journal of Environmental Research and Public Health*, Vol. 16, No 6, doi:10.3390/ijerph16060940.

European Commission, Directorate-General for Research and Innovation (2017), *Europe's Future: Open Innovation, Open Science, Open to the World: Reflections of the Research, Innovation and Science Policy Experts (RISE) High Level Group*, Publications Office of the European Union, Luxembourg, doi:10.2777/348700.

European Commission (n.d.), 'Biofuels' (https://ec.europa.eu/energy/topics/renewable-energy/biofuels/overview_en).

Fecher, B. and Friesike, S. (2014), 'Open science: one term, five schools of thought', in Bartling, S. and Friesike, S. (eds), *Opening Science*, Springer, Cham, pp. 17–47.

Fleming, L. and Sorenson, O. (2001), 'Technology as a complex adaptive system: evidence from patent data', *Research Policy*, Vol. 30, No 7, pp. 1019–1039.

Fortunato, S., Bergstrom, C. T., Börner, K., Evans, J. A., Helbing, D., Milojević, S., Petersen, A. M., Radicchi, F., Sinatra, R., Uzzi, B., Vespignani, A., Waltman, L., Wang, D. and Barabási, A.-L. (2018), 'Science of science', *Science*, Vol. 359, No 6379, doi:10.1126/science.aao0185.

Garnier, J.-P. (2008), 'Rebuilding the R & D engine in big pharma', *Harvard Business Review*, Vol. 86, No 5, pp. 68–76, 128.

Gassmann, O. and Reepmeyer, G. (2005), 'Organizing pharmaceutical innovation: from science-based knowledge creators to drug-oriented knowledge brokers', *Creativity and Innovation Management*, Vol. 14, No 3, pp. 233–245, doi:10.1111/j.1467-8691.2005.00344.x.

Goel, R. K. and Göktepe-Hultén, D. (2021), 'Innovation by foreign researchers: relative influences of internal versus external human capital', *Journal of Technology Transfer*, Vol. 46, No 1, pp. 258–276, doi:10.1007/s10961-019-09771-8.

Gold, E. R. (2021), 'The fall of the innovation empire and its possible rise through open science', *Research Policy*, Vol. 50, No 5, doi:10.1016/j.respol.2021.104226.

Gordon, R. J. (2016), *The Rise and Fall of American Growth: The U.S. standard of living since the civil war*, Princeton University Press, Princeton, NJ.

Griliches, Z. (1958), 'Research costs and social returns: hybrid corn and related innovations', *Journal of Political Economy*, Vol. 66, No 5, pp. 419–431.

Habib, M., Abbas, J. and Noman, R. (2019), 'Are human capital, intellectual property rights, and research and development expenditures really important for total factor productivity? An empirical analysis', *International Journal of Social Economics*, Vol. 46, No 6, pp. 756–774, doi:10.1108/IJSE-09-2018-0472.

Hall, B. H., Lotti, F. and Mairesse, J. (2013), 'Evidence on the impact of R & D and ICT investments on innovation and productivity in Italian firms', *Economics of Innovation and New Technology*, Vol. 22, No 3, pp. 300–328, doi:10.1080/10438599.2012.708134.

Henderson, R. and Cockburn, I. (1996), 'Scale, scope, and spillovers: the determinants of research productivity in drug discovery', *RAND Journal of Economics*, Vol. 27, No 1, pp. 32–59, doi:10.2307/2555791.

Hermosilla, M. (2021), 'Rushed innovation: evidence from drug licensing', *Management Science*, Vol. 67, No 1, pp. 257–278, doi:10.1287/mnsc.2019.3530.

Hicks, D., Wouters, P., Waltman, L., De Rijcke, S. and Rafols, I. (2015), 'Bibliometrics: the Leiden Manifesto for research metrics', *Nature*, Vol. 520, No 7548, pp. 429–431.

Hoos, A., Anderson, J., Boutin, M., Dewulf, L., Geissler, J., Johnston, G., Joos, A., Metcalf, M., Regnante, J., Sargeant, I., Schneider, R. F., Todaro, V. and Tougas, G. (2015), 'Partnering with patients in the development and lifecycle of medicines: a call for action', *Therapeutic Innovation and Regulatory Science*, Vol. 49, No 6, pp. 929–939, doi:10.1177/2168479015580384.

Jones, B. F. (2009), 'The burden of knowledge and the "death of the renaissance man": is innovation getting harder?', *Review of Economic Studies*, Vol. 76, No 1, pp. 283–317, doi:10.1111/j.1467-937X.2008.00531.x.

Kissin, I. (2010), 'The development of new analgesics over the past 50 years: a lack of real breakthrough drugs', *Anesthesia and Analgesia*, Vol. 110, No 3, pp. 780–789, doi:10.1213/ANE.0b013e3181cde882.

Koning, R., Samila, S. and Ferguson, J.-P. (2021), 'Who do we invent for? Patents by women focus more on women's health, but few women get to invent', *Science*, Vol. 372, No. 6548, pp. 1345–1348, doi:10.1126/SCIENCE.ABA6990.

Kortum, S. S. (1997), 'Research, patenting, and technological change', *Econometrica*, Vol. 65, No 6, pp. 1389–1419, doi:10.2307/2171741.

Koutroumpis, P., Leiponen, A. and Thomas, L. D. W. (2020), 'Small is big in ICT: the impact of R & D on productivity', *Telecommunications Policy*, Vol. 44, No 1, doi:10.1016/j.telpol.2019.101833.

Lanjouw, J. O. and Schankerman, M. (2004), 'Patent quality and research productivity: measuring innovation with multiple indicators', *Economic Journal*, Vol. 114, No 495, pp. 441–465, doi:10.1111/j.1468-0297.2004.00216.x.

Machlup, F. (1962), *The production and distribution of knowledge in the United States*, Vol. 278, Princeton University Press, Princeton, NJ.

Mazzucato, M. (2021), *Mission Economy – A moonshot guide to changing capitalism*, Allen Lane, London.

Mignani, S., Huber, S., Tomás, H., Rodrigues, J. and Majoral, J.-P. (2016), 'Why and how have drug discovery strategies in pharma changed? What are the new mindsets?', *Drug Discovery Today*, Vol. 21, No 2, pp. 239–249, doi:10.1016/j.drudis.2015.09.007.

MIT Sloan School of Management (2021), 'What are industry verticals?' (https://cdo.mit.edu/blog/2021/06/17/what-are-industry-verticals/).

Mokyr, J. (2005), 'Useful knowledge as an evolving system: the view from economic history', in Blume, L. E. and Durlauf, S. N. (eds), *The Economy as an Evolving Complex System III*, Oxford University Press, Oxford (http://ideas.repec.org/p/esi/evopap/2004-23.html).

Nagaraj, D. R. and Farinato, R. S. (2016), 'Evolution of flotation chemistry and chemicals: a century of innovations and the lingering challenges', *Minerals Engineering*, Vols 96–97, pp. 2–14, doi:10.1016/j.mineng.2016.06.019.

NESTA (National Endowment for Science, Technology and the Arts) (2021), 'Randomised controlled trials' (http://toolkit.innovationgrowthlab.org/home).

OECD (Organisation for Economic Co-operation and Development) (2015), 'Making open science a reality', *OECD Science, Technology and Industry Policy Papers*, No 25, doi:10.1787/5jrs2f963zs1-en.

Owens, P. K., Raddad, E., Miller, J. W., Stille, J. R., Olovich, K. G., Smith, N. V., Jones, R. S. and Scherer, J. C. (2014), 'A decade of innovation in pharmaceutical R & D: the Chorus model', *Nature Reviews Drug Discovery*, Vol. 14, No 1, pp. 17–28, doi:10.1038/nrd4497.

Pammolli, F., Magazzini, L. and Riccaboni, M. (2011), 'The productivity crisis in pharmaceutical R & D', *Nature Reviews Drug Discovery*, Vol. 10, No 6, pp. 428–438, doi:10.1038/nrd3405.

Pammolli, F., Righetto, L., Abrignani, S., Pani, L., Pelicci, P. G. and Rabosio, E. (2020), 'The endless frontier? The recent increase of R & D productivity in pharmaceuticals', *Journal of Translational Medicine*, Vol. 18, No 1, doi:10.1186/s12967-020-02313-z.

Paul, S. M., Mytelka, D. S., Dunwiddie, C. T., Persinger, C. C., Munos, B. H., Lindborg, S. R. and Schacht, A. L. (2010), 'How to improve

RD productivity: the pharmaceutical industry's grand challenge', *Nature Reviews Drug Discovery*, Vol. 9, No 3, pp. 203–214, doi:10.1038/nrd3078.

Pavitt, K. (1984), 'Sectoral patterns of technical change: towards a taxonomy and a theory', *Research Policy*, Vol. 13, pp. 343–374.

Pisano, G. P. (2006), 'Can science be a business? Lessons from biotech', *Harvard Business Review*, Vol. 84, No 10, pp. 114–125, 150.

Plenge, R. M. (2016), 'Disciplined approach to drug discovery and early development', *Science Translational Medicine*, Vol. 8, No 349, doi:10.1126/scitranslmed.aaf2608.

Poitiers, N. F. and Weil, P. (2021), 'A new direction for the European Union's half-hearted semiconductor strategy', *Policy Contributions*, No 17, Bruegel, Brussels (https://www.bruegel.org/wp-content/uploads/2021/07/PC-2021-17-semiconductors-.pdf).

Rafols, I., Noyons, E., Confraria, H. and Ciarli, T. (2021), 'Visualising plural mappings of science for sustainable development goals (SDGs)', *SocArXiv*, doi:10.31235/osf.io/yfqbd.

Ravichandran, T., Han, S. and Mithas, S. (2017), 'Mitigating diminishing returns to R & D: the role of information technology in innovation', *Information Systems Research*, Vol. 28, No 4, pp. 812–827, doi:10.1287/isre.2017.0717.

Raymond, W., Mairesse, J., Mohnen, P. and Palm, F. (2015), 'Dynamic models of R & D, innovation and productivity: panel data evidence for Dutch and French manufacturing', *European Economic Review*, Vol. 78, pp. 285–306, doi:10.1016/j.euroecorev.2015.06.002.

Reed, M. S., Ferré, M., Martin-Ortega, J., Blanche, R., Lawford-Rolfe, R., Dallimer, M. and Holden, J. (2021), 'Evaluating impact from research: a methodological framework', *Research Policy*, Vol. 50, No 4, 104147.

RIN (Research Information Network) / NESTA (2010), *Open to All? Case studies of openness in research*, RIN and NESTA, London.

Saha, A. and Ciarli, T. (2018), 'Innovation, structural change, and inclusion. A cross country PVAR analysis', *SPRU Working Papers*, No 2018–1, Science and Technology Policy Research, University of Sussex, Brighton.

Sarewitz, D. (2016), 'Saving science', *The New Atlantis*, Vol. 49, pp. 4–40, doi:10.18601/01245996.v19n37.03.

Serban, A. C. and Lytras, M. D. (2020), 'Artificial intelligence for smart renewable energy sector in Europe – smart energy infrastructures for next generation smart cities', *IEEE Access*, Vol. 8, pp. 77364–77377, doi:10.1109/ACCESS.2020.2990123.

Sun, Z., Wang, X., Liang, C., Cao, F. and Wang, L. (2021), 'The impact of heterogeneous environmental regulation on innovation of high-tech enterprises in China: mediating and interaction effect', *Environmental Science and Pollution Research*, Vol. 28, No 7, pp. 8323–8336, doi:10.1007/s11356-020-11225-w.

van der Greef, J. and McBurney, R. N. (2005), 'Rescuing drug discovery: *in vivo* systems pathology and systems pharmacology', *Nature Reviews Drug Discovery*, Vol. 4, No 12, pp. 961–967, doi:10.1038/nrd1904.

Wallace, M. L. and Rafols, I. (2015), 'Research portfolio analysis in science policy: moving from financial returns to societal benefits', *Minerva*, Vol. 53, No 2, pp. 89–115.

Wang, C.-H., Lu, Y.-H., Huang, C.-W. and Lee, J.-Y. (2013), 'R & D, productivity, and market value: an empirical study from high-technology firms', *Omega*, Vol. 41, No 1, pp. 143–155, doi:10.1016/j.omega.2011.12.011.

Williamson, O. E. (1981), 'The economics of organization: the transaction cost approach', *American Journal of Sociology*, Vol. 87, No 3, pp. 548–577.

Woltjer, G., van Galen, M. and Logatcheva, K. (2021), 'Industrial innovation, labour productivity, sales and employment', *International Journal of the Economics of Business*, Vol. 28, No 1, pp. 89–113, doi:10.1080/13571516.2019.1695448.

Yegros-Yegros, A., van de Klippe, W., Abad-Garcia, M. F. and Rafols, I. (2020), 'Exploring why global health needs are unmet by research efforts: the potential influences of geography, industry and publication incentives', *Health Research Policy and Systems*, Vol. 18, No 47, doi:10.1186/s12961-020-00560-6.

Ziman, J. M. (2000), *Technological Innovation as an Evolutionary Process*, Cambridge University Press, Cambridge.

ANNEXES

Annex 1: Systematisation of literature review and references – Phase 1: Scientometric framework (publications and patents)

Inputs	Outputs	Definition	Outcomes	Breaks
Macro	**Publications**	**Publication based**	**Scientific**	**Scientific**
Research funding (Gulbrandsen and Smeby, 2005; Jacob and Lefgren, 2011; Wang and Shapira, 2015; Myers, 2020) HERD/GERD (King, 2004) Funding intensity/variety (Gök et al., 2016) GDP/GDP per capita (Hohmann et al., 2017) Number of papers (funding	Journal articles (Dundar and Lewis, 1998; Lee and Bozeman, 2005; Breschi et al., 2007; Jacob and Lefgren, 2011; Horta and Santos, 2016; Kwiek, 2016; Myers, 2020)	Number of publications per researcher (Dundar and Lewis, 1998; Lee and Bozeman, 2005; Breschi et al., 2007; Jacob and Lefgren, 2011; Horta and Santos, 2016; Kwiek, 2016) Number of publications per funding (Jacob and Lefgren, 2011) 'The [scientific] output produced in a given period per unit of production factors used to produce it' (Abramo and Angelo, 2014; see fractional scientific strength formula) 'ratios between output indicators and the number of university staff members in the survey period' (Abramo et al., 2009)	H-index (Hirsch, 2005) Contribution to relevant topics (Myers, 2020)	

Inputs	Outputs	Definition	Outcomes	Breaks
proxy) (Popp, 2017)		'Research efficiency or productivity: indicators that relate research output to input. Typical examples of metrics are the number of published articles per full time equivalent (FTE) researcher, or the number of citations per Euro spent on research.' (Moed and Halevi, 2015)		
Organisation	**Citations**	**Citation based**	**Public engagement**	**Citation based**
Reporting guidelines (Vilaró et al., 2019) Size and age of the university (Blasi et al., 2018) Organisation (Ma et al., 2014) Training (variety of instructional programmes; level of instructional programmes; instructors and research staff body; and student body) (Phusavat,	(Jacob and Lefgren, 2011; Gök et al., 2016; Popp, 2017) Normalised citation impact (Lariviere and Gingas, 2010; Abramo and Angelo, 2014; Waltman, 2016) Highly cited papers (Sandström et al., 2016) Impact factor (Wang and	Citations per researcher (Allison, 1980; Eysenbach, 2011; Li et al., 2013) Citations per paper (Ruíz-Pérez et al., 2015) Citations per funding (Jacob and Lefgren, 2011; Wang and Shapira, 2015; Gök et al., 2016)	Public engagement with research outputs (proxied by altmetrics) (Bornmann, 2014)	Most cited 1 %/3.5 %/5 % by field and year of publication (King, 2004; Uzzi et al., 2013; Sandström and van Besselaar, 2016)

Inputs	Outputs	Definition	Outcomes	Breaks
2011)	Shapira, 2015)			
Individual Early career (during PhD) publication (Horta and Santos, 2016) Individual characteristics: gender, age, nationality, academic ranking, experience in higher education and time spent on research (Costas et al., 2010; Lariviere et al., 2011; Sotudeh and Khoshian, 2014; Sinatra et al., 2016; Khalil, 2019) Being an inventor (patentee) (Breschi et al., 2007; Azoulay et al., 2009)	**Patents** (Popp, 2017)	**Patent based** Patents per paper (Popp, 2017) Patents per funding (Popp, 2017)	**Challenges** Clean energy (Popp, 2017)	**Patent based** New patents (Popp, 2017)
Focus	**Altmetrics** (citations)	**Altmetrics based**	**Economic**	

Inputs	Outputs	Definition	Outcomes	Breaks
Research priorities/focus (Marshall, 2004; Myers, 2020)	Tweets (Larivière et al., 2015) Mendeley (Larivière et al., 2015)	Number of tweets per paper (Ortega, 2017)		
Collaborations Knowledge recombination / interdisciplinary (Larivière and Gingras, 2010; Uzzi et al., 2013) Research programme (interdisciplinary versus disciplinary) (Gartner et al., 2014) Social capital / network centrality (Abbasi et al., 2011; Li et al., 2013)	**Funding** Research opportunities (Myers, 2020) Future funding (Jacob and Lefgren, 2011)	**Funding** Applications per grants (Myers, 2020) Future funding per past funding (Jacob and Lefgren, 2011)	**Individual**	

Inputs	Outputs	Definition	Outcomes	Breaks
Number of authors and order of authors (Lee and Bozeman, 2005; Abramo et al., 2009; Abramo et al., 2013)				
Outlet Journal characteristics (periodicity and regularity; peer review; impact factor; abstracting and indexing services) (Ruiz-Perez et al., 2015) Journal Twitter accounts (Ortega, 2017)	**Innovations**		**Innovations**	**Innovations**
Tools Type of computer used (Zainab and Meadows, 1999)	**Non-academic**	**Impact**		
Other	**Other**			

NB: GDP, gross domestic product; GERD, gross domestic expenditure on R & D; HERD, higher education expenditure on R & D.

Annex 2: Categories

A2.1. Inputs

Human capital

- Education
- Tertiary education
- R & D personnel

Infrastructure

- ICT
- Labs

Business

- Innovation linkages
- Knowledge absorption
- Management
- efficiency
- Firms' characteristics
- Value added

Funding

- Private funding
- Public funding
- Foreign direct investment
- Gross domestic expenditure on R & D

Knowledge

- Scientific knowledge
- Non-scientific knowledge
- Knowledge flows
- Technology development
- Invention

Research collaboration

Intellectual property

A2.2. Outputs

Challenges

Education

Poverty

Innovation

New molecular entities

Innovations

Ideas

New products

New processes

New drugs on the market

Organisational innovation

New plant variety

Innovator firms

Economic

Crop productivity

Job creation

Sales and revenue

Gross domestic product

Labour productivity

Market value

Exports

Income

Industry productivity

Firm productivity

Total factor productivity

Health

New drugs approved by official organisations

Patient outcomes

Environmental

CO_2 emissions

Patents

A2.3. Factors hindering research productivity

Fast-expanding endless frontier. New knowledge is essential for innovation, but as the frontier expands new knowledge is more difficult to achieve and more investments and talents are needed (Bush, 1945; Kortum, 1997; Jones, 2009; Bloom et al., 2020; Chu and Evans, 2021)

Cost. Cost of R & D is increased (for whatever input is needed, except for human capital).

Human capital. There are issues related to attracting and retaining highly skilled workers. In addition, the educational burden expands, as new generations of researchers must learn more and accrue more knowledge to contribute to the expansion of the knowledge frontier.

Knowledge frontier. There is increased difficulty in exploring a knowledge frontier that keeps advancing and expanding, requiring the combination of different sources of knowledge.

Knowledge combination. Although innovation is a process of knowledge recombination, and radical innovations tend to emerge from the combination of more different knowledge components, such combinations are risky and are increasingly difficult to produce (Ziman, 2000; Fleming and Sorensen, 2004; Arthur, 2009).

Managing collaborations. This refers to any issue related to managing collaborations between teams (from the same or different disciplines).

Disciplinarity. Inherent differences between disciplines keep expanding as specialisation increases at the knowledge frontier.

Path dependence. There is a lock-in in historical patterns of research, in terms of methods and topics, among other things.

Siloed knowledge. Researchers specialise in specific areas of knowledge or disciplines and there is a lack of engagement beyond those.

Market pressure. Incentives are often driven by profits and not the need to expand knowledge to improve social welfare (Wallace and Rafols, 2015; Sarewitz, 2016; Gold, 2021).

Capitalism pressure. Incentives are provided to increase profits and minimise innovation risks.

Competition. There is high competition pressure that produces incentives for short-term, high-reward rather than long-term investment strategies (in industry and academia).

R & D incentives. Aside from market pressure, several policies shape innovation incentives in ways that are not aligned with radical innovations or innovations for the public good (Brown et al., 2017; Fortunato et al., 2018; Koutroumpis et al., 2020).

Evaluation pressure. Incentive are provided to prioritise publishable research.

Regulation. This includes any issue related to the regulation of the innovation system (not included in IPR)

IPR. This includes any issue related to improving the regulation of property rights (not included in 'Closed science')

R & D Routines. Innovation processes and routines have changed substantially over time and vary across sectors. As new technologies and new organisations emerge, R & D processes need to adapt (see, for example, studies in the area of artificial intelligence (Cockburn et al., 2019) and the pharmaceutical industry (Henderson and Cockburn, 1996; Owens et al., 2014; Cobb et al., 2019).

Closed science. There are barriers to accessing knowledge produced in research and non-scientists are excluded from the knowledge production process.

Firm management. This refers to the overall management of the organisation (not of the R & D lab).

R & D management. This includes any issue related to managing research or R & D labs, across and within organisations, not included in 'Collaboration issues'.

R & D process. This includes any specific issue related to the methods used in conducting research (not how it is managed), for instance research pipelines, the identification of technical bottlenecks, optimisation issues, issues in upgrading technology and the roles of research staff.

A2.4. Potential remedies to improve RP

Improving access to human capital. Different strategies can be used to improve access to or the retention of skills and talents in R & D (Goel and Göktepe-Hultén 2021; Habib et al., 2019;).

Human capital. Improve all aspects of human capital, such as skills, education and the retention of talent.

Inclusion. Improve the inclusion of talents with less opportunities.

Setting strategies for R & D priorities. To combat hindering factors that push for increased specialisation and siloed knowledge, there are several ways to modify the incentives of organisations and scientists to reduce (or increase) specialisation (Cuatrecasas, 2006); reduce the focus on bibliometric evaluations (Bhattacharya and Packalen, 2020); and increase the focus on diversification (Kissin, 2010), paradigm shifts (van der Greef and McBurney, 2005; Jones, 2009) and the societal impacts of R & D (Hoos et al., 2015).

Diversification. Increase the scope of research and exploration.

Incremental innovation. Focus on incremental innovation.

Paradigm shift. Focus on radical innovations / new paradigms.

Research evaluation. Divert incentives away from prioritising on research performance.

Social impact orientation. Foster research with an aim of benefiting stakeholders beyond academia, in terms of economic, environmental and cultural transformations.

Specialisation. Reduce the scope of research.

Improving R & D routines. Specific aspects of R & D processes can be improved to combat hindering factors in various ways. These include using new technologies and methods (Pammolli et al., 2020), providing open access and improving reproducibility (Gassmann and Reepmeyer, 2005; Bowen and Casadevall, 2015), and improving collaboration (Baba et al., 2009; Belderbos et al., 2015).

Collaborations. Improve collaboration across teams, disciplines and organisations.

New methods. This includes any new method applied to R & D, specific to sectors, organisations or disciplines.

Open access. Allow readers to obtain bibliographical research outputs without any barriers, especially payment.

Interdisciplinarity. Integrate knowledge from different academic disciplines.

R & D management. Improve the operational aspects of the management of R & D labs, teams or processes.

R & D organisation. Improve the governance of R & D, including science, technology and innovation systems, hierarchies, relationships, coordination, roles and power.

R & D process. Improve the way in which research is conducted and organised, beyond methods.

Technologies. Use new technologies (e.g. artificial intelligence).

Increasing R & D funding. Remedies in this category increase private or public funding to counteract the diminishing returns of knowledge production (Henderson and Cockburn, 1996; Raymond et al., 2015; Bloom et al., 2020).

Private funding. More business expenditure on R & D (BERD) is needed.

Public funding. More public funding is needed.

Improving management and organisation. Beyond R & D processes, improvements could be made in the management and organisation of research-intensive organisations and their research labs (Paul et al., 2010; Cummings and Knott, 2018).

Firm management. Improve the overall management of the organisation.

Firm organisation. Improve the organisation of the firm's production.

Market strategies. Adopt strategies to improve sales/profits.

Improving governance. Several hindering factors could be addressed with policies, such as IPR (Brown et al., 2017; Habib et al., 2019), better regulations and several policy instruments to steer incentives (Pammolli et al., 2020; Bowen and Casadevall, 2015; Pammolli et al., 2011; Garnier 2008;).

IPR protection. Increase protection through intellectual property (patents, etc.).

Policy instruments. Conduct public interventions to steer R & D (not included in 'IPR protection'.

Regulation. Improve the regulation of markets/sectors (not included in 'IPR protection').

A2.5. Sectors

SIC Revision 4 – two-digit	Identified in the literature as
Agriculture, forestry and fishing (01–03)	Agriculture
Mining and quarrying (01–09)	Mining
Manufacture of textiles, wearing apparel, leather and related products (13–15)	Clothes
Manufacture of chemicals and chemical products (20)	Chemicals
Manufacture of pharmaceuticals, and medicinal chemical and botanical products (21)	Pharma, biomed, biotech
Manufacture of computer, electronic and optical products (26)	ICT and electronics
Manufacture of machinery and equipment (28)	Machinery
Electricity, gas, steam and air conditioning supply (35)	Renewable energy
Construction (41–43)	Construction industry
Professional, scientific and technical activities (69–75)	Consultancy

SIC Revision 4 – two-digit	Identified in the literature as
Scientific R & D (72)	University research, academia
Administrative and support service activities (77–82)	Government
Education (85)	
Cross-sectoral	
Not defined	

Annex 3: Description of innovation framework sample

Table 31. Number of papers per category type

Category type	Number of papers
Decline (includes 'not addressed')	83
Productivity (4 are classified as other)	76
Input	71
Output	71
Sector (includes 'all sectors')	64
Remedy	50
Remedy Level0	50
Hindering factor	42
Hindering factor Level0	42

Table 32. Number of papers addressing all four main variables – inputs, outputs, hindering factors and remedies – by definition of RP

Productivity definition	Number of papers
Innovation based	14
Economics based	9
Patent based	6
Innovation based; impact based	1
Impact based; economics based	1
Economics based; impact based	1
Total	32

Table 33. Number of papers addressing all four main variables – inputs, outputs, hindering factors and remedies – by sector

Sector (as referenced in the literature)	Number of papers
Pharma	8
All sectors	7
Not defined	4
ICT	2
Biomedical	2
Manufacturing	1
Pharma; biomedical	1
Agricultural	1
Mining	1

Biotech; pharma	1
Photocatalyst	1
Chemicals; mechanical; electronics; health; biotech; pharma; ICT	1
Academia	1
High-tech	1
Total	32

Annex 4: Survey questionnaire

Research productivity, open science, and social impact

Fields marked with * are mandatory.

Welcome

Participant Information & Codebook - Survey on research productivity

What is this survey about?

With this survey we are seeking to collect views from a range of experts from academia, policy and funding, on whether research productivity has declined in the last few decades. We ask experts' opinion on what might be the hindering factors explaining such decline, and the possible remedies to address these hindering factors. In addition, the survey asks whether open science (OS) practices could contribute to increasing research productivity, by addressing the hindering factors that respondents identify as responsible for research productivity decline. Or, whether OS practices may themselves constitute a hindering factor. Finally, we ask views on whether higher research productivity might lead to a stronger societal impact.

Our findings will be shared with the European Commission and some of the world's primary funders of science and innovation. Taking part in this survey is an opportunity to share views with them and influence their funding decisions.

How long does it take?

The survey takes 15-20 minutes to complete on average. This will also depend on the extent of responses to open questions.

How will my responses be used and stored?

The results from this survey will be used in a European Commission study on factors impeding the productivity of research and the prospects for open science policies to improve the ability of the Research and Innovation system to transform financial investment in research into valuable outputs such as break-through innovations. This research has been approved by the Sussex University Sciences & Technology Cross-Schools Research Ethics Committee ER/HBP48/4.

The survey is anonymous. All personal information collected during the course of the research will be kept strictly confidential. Respondents cannot be identified in any ensuing reports or publications. The controller for this project is the University of Sussex.

Contacting us

The findings will be published in late 2021 in European Commission report. Any questions or concerns about the way this research is conducted or personal information is managed, please contact the survey Investigator Dr. Tommaso Ciarli at t.ciarli@sussex.ac.uk.

Consent to participate
Please tick the box below to indicate that you consent to participate in this study and that you:

- Have read the Participant Information on the previous pages and understand what the research involves.
- Understand that your participation is voluntary and that you are free to withdraw from the survey at any time, without having to give a reason, and without any consequences.
- Understand that you are giving the research team the right to use and make available the information you share (though not attributed to you and your organisation without further consent) in the following ways:
    - Publications in academic journals and other media; or public lecture talks.
    - Reports, online media, blogs, policy briefings

* Consent

○ I consent ○ Please, stop here

A. Respondent profile

* A1. Disciplinary backgroung

☐ Agricultural sciences
☐ Physical sciences and engineering
☐ Social sciences and humanities
☐ Medical and health sciences
☐ Life and earth sciences
☐ Mathematical and computer sciences
☐ Other

Please specify discipline

* A2. What best describes the type of institution you work for?

○ Research (e.g. university; research institute; think tank)
○ Public sector (e.g. government; Military forces)
○ Private sector (e.g. business enterprise; self-employed)
○ Not-for-profit (e.g. NGOs)
○ Does not apply (unemployed, retired)
○ Other

Please, specify if other

* A3. What best describes your gender?

○ Female

- Male
- Other
- Prefer not to say

* A4. on which regions has your work focused?

- Europe
- Asia
- Africa
- Northern America
- Latin America and the Caribbean
- Oceania
- No specific region

B. Research productivity and hindering factors

Definition

We define research productivity as **the ratio between research inputs** (e.g. funding and researchers time) **and innovative outputs** (e.g. new technologies, patents, drugs, solutions to problems). Improving research productivity implies improving the efficiency of the research system/funding in generating /developing innovations, which in some cases may also lead to socio-economic benefits. We are particularly interested in your answers considering tangible **innovative outputs**, beyond publications.

* B1 In your experience, and/or according to your research, do you believe that research productivity has declined in the past 10 years?

- Yes, it has declined
- No, it has remained the same
- No, it has increased
- I do not know

B1.1 In which sector of the economy do you think research productivity has declined?

* B2 Sporadically, research produces discoveries with major impact on society, sometimes referred to as **bre akthroughs**. In your experience and according to your research, do you think that **the number and/or value of breakthroughs has declined** in the past 10 years?

- Yes, it has declined
- No, it has remained the same
- No, it has increased
- I do not know

_

B3 What are, in your opinion, two key factors that may hinder research productivity? **Please, take note of your answers as these hindering factors will be referenced in subsequent questions**

* B3.1 Hindering factor 1:

* B3.2 Hindering factor 2

B4. For each one of the two hindering factors that you have identified in the previous question, please indicate what may be the main remedy to address them and increase research productivity

* B4.1 Remedy to address hindering factor 1

* B4.2 Remedy to address hindering factor 2

C. Research productivity and Open Science (OS)

For each of the open science practices listed below, please identify whether they may contribute to **increasi ng research productivity**. If so, which of the two hindering factors that you have identified in question B3 (previous section above) are addressed by the OS practice, if any?

C1 Open access and sharing of research outputs

* C1.1 In my experience, Open Access to scientific publications may contribute to increasing research productivity

By Open Access we understand principles and practices that enable the distribution of research publications free of cost and other barriers to readers, through any model (green, gold, hybrid, diamond, etc.)

True False I do not know

* Which of the two hindering factors that you have identified in question B3 are addressed by this OS practice, if any?

Hindering factor 1 Hindering factor 2 Other hindering factor (s)

* C1.2 In my experience, operationalization of FAIR data principles (findable, accessible, interoperable and reusable) may contribute to increasing research productivity

True False I do not know

* Which of the two hindering factors that you have identified in question B3 are addressed by this OS practice, if any?

☐ Hindering factor 1 ☐ Hindering factor 2 ☐ Other hindering factor (s)

* C1.3 In my experience, open licences may contribute to increasing research productivity

By open licenses we understand intellectual property mechanisms that allow reusing research outputs. For example, creative commons licenses.

○ True ○ False ○ I do not know

* Which of the two hindering factors that you have identified in question B3 are addressed by this OS practice, if any?

☐ Hindering factor 1 ☐ Hindering factor 2 ☐ Other hindering factor (s)

* C1.4 In my experience, documenting and sharing workflows and methods openly may contribute to increasing research productivity

We refer to practices of documentation of the research process, for example, GitLab or open notebooks such as LabTrove

○ True ○ False ○ I do not know

* Which of the two hindering factors that you have identified in question B3 are addressed by this OS practice, if any?

☐ Hindering factor 1 ☐ Hindering factor 2 ☐ Other hindering factor (s)

C2 Research Collaboration

* C2.1 In my experience, interdisciplinarity may contribute to increasing research productivity

We understand interdisciplinary research as research processes that integrate methods and practices from two or more disciplines or bodies of specialised knowledge

○ True ○ False ○ I do not know

* Which of the two hindering factors that you have identified in question B3 are addressed by this OS practice, if any?

☐ Hindering factor 1 ☐ Hindering factor 2 ☐ Other hindering factor (s)

* C2.2 In my experience, networked science and crowdsourcing science may contribute to increasing research productivity

We understand networked or crowdsourcing science as research projects characterised by a wide base of potential contributors who could be involved in particular tasks of the research cycle and who share their research inputs and outputs openly in digital infrastructure

○ True ○ False ○ I do not know

* Which of the two hindering factors that you have identified in question B3 are addressed by this OS practice, if any?

☐ Hindering factor 1 ☐ Hindering factor 2 ☐ Other hindering factor (s)

* C2.3 In my experience, citizen science and transdisciplinary research may contribute to increasing research productivity

We understand citizen science and transdisciplinary research as projects that involve collaboration with communities/citizens in different stages of the scientific processes and/or that integrate knowledge from scientific disciplines and non-academic communities.

○ True ○ False ○ I do not know

* Which of the two hindering factors that you have identified in question B3 are addressed by this OS practice, if any?

☐ Hindering factor 1 ☐ Hindering factor 2 ☐ Other hindering factor (s)

C3 Engaging and translating

C3.1 In my experience, public communication of science may contribute to increasing research productivity

We understand public communication of science as engaging with mass and social media to disseminate research outputs such as newspapers articles, briefings, blog pieces, podcasts, social networks posts, etc.

○ True ○ False ○ I do not know

* Which of the two hindering factors that you have identified in question B3 are addressed by this OS practice, if any?

☐ Hindering factor 1 ☐ Hindering factor 2 ☐ Other hindering factor (s)

C3.2 In my experience, interactive activities to include society into scientific discussions may contribute to increasing research productivity

We refer to interaction activities responding to social concerns or interests that contribute to the social valorisation of science such as science clubs, science shops, science observatories, etc.

○ True ○ False ○ I do not know

* Which of the two hindering factors that you have identified in question B3 are addressed by this OS practice, if any?

☐ Hindering factor 1 ☐ Hindering factor 2 ☐ Other hindering factor (s)

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* C4 Which of these Open Science practices (listed below) may **hinder** research productivity? Please tick as many as relevant

☐ Open access to scientific publications
☐ Operationalization of FAIR data principles (findable, accessible, interoperable and reusable) also across sectors
☐ Open licences: avoid the use of intellectual property rights that restrict access to knowledge (i.e. avoid exclusive rights on research outputs)
☐ Documenting and sharing workflows and methods openly
☐ Interdisciplinarity. It involves contributions from different disciplines
☐ Networked science and crowdsourcing science
☐ Citizen science and transdisciplinary research. Both practices involve collaboration with communities/citizens in different stages of the scientific processes.

- [ ] Public communication of science: general articles, briefings, blog pieces, social networks
- [ ] Interactive activities to include society into scientific discussions: science shops, science clubs, etc.
- [ ] None of the above

---

* C5 Could you provide examples of how OS practices improve research productivity in your field? please add "none" if you are not aware of any

* C6 What are the main constraints for the adoption of OS practices? please add "none" if you are not aware of any

---

D. Research productivity and societal impact

We define societal impact as the contribution of research to societal challenges (e.g. economic growth, more and better jobs, health, sustainable agriculture, food security, climate action) or the Sustainable Development Goals (e.g. zero hunger, gender equality, reduced inequalities, clean water and sanitation)

* D1 In your experience, to what extent a higher **research productivity** may contribute to a stronger **societal impact**?

- To a very small extent
- To a small extent
- To a moderate extent
- To a large extent
- To a very large extent
- Does not contribute
- I do not know

Please, briefly describe why if you selected an option other than I do not know.

D2 In your experience, to what extent each of the following **open science (OS)** practices may contribute to increasing the **societal impact** of research?

* D2.1 Open access to scientific publications

By Open Access we understand principles and practices that enable the distribution of research publications free of cost and other barriers to readers, through any model (green, gold, hybrid, diamond, etc.)

- To a very small extent
- To a small extent
- To a moderate extent

- To a large extent
- To a very large extent
- Does not contribute
- I do not know

* D2.2 Operationalization of FAIR data principles (findable, accessible, interoperable and reusable) also across sectors

- To a very small extent
- To a small extent
- To a moderate extent
- To a large extent
- To a very large extent
- Does not contribute
- I do not know

* D2.3 Open licences: avoid the use of intellectual property rights that restrict access to knowledge (i.e. avoid exclusive rights on research outputs)

By open licenses we understand intellectual property mechanisms that allow reusing research outputs. For example, creative commons licenses

- To a very small extent
- To a small extent
- To a moderate extent
- To a large extent
- To a very large extent
- Does not contribute
- I do not know

* D2.4 Documenting and sharing workflows and methods openly

We refer to practices of documentation of the research process, for example, GitLab or open notebooks such as LabTrove

- To a very small extent
- To a small extent
- To a moderate extent
- To a large extent
- To a very large extent
- Does not contribute
- I do not know

* D2.5 Interdisciplinarity. It involves contributions from different disciplines

We understand interdisciplinary research as research processes that integrate methods and practices from two or more disciplines or bodies of specialised knowledge

- To a very small extent
- To a small extent
- To a moderate extent
- To a large extent
- To a very large extent
-

- Does not contribute
- I do not know

* D2.6 Networked science and crowdsourcing science.

We understand networked or crowdsourcing science as research projects characterised by a wide base of potential contributors who could be involved in particular tasks of the research cycle and who share their research inputs and outputs openly in digital infrastructure

- To a very small extent
- To a small extent
- To a moderate extent
- To a large extent
- To a very large extent
- Does not contribute
- I do not know

* D2.7 Citizen science and transdisciplinary research. Both practices involve collaboration with communities /citizens in different stages of the scientific processes

We understand citizen science and transdisciplinary research as projects that involve collaboration with communities/citizens in different stages of the scientific processes and/or that integrate knowledge from scientific disciplines and non-academic communities

- To a very small extent
- To a small extent
- To a moderate extent
- To a large extent
- To a very large extent
- Does not contribute
- I do not know

* D2.8 Public communication of science: general articles, briefings, blog pieces, social networks

We understand public communication of science as engaging with mass and social media to disseminate research outputs such as newspapers articles, briefings, blog pieces, podcasts, social networks posts, etc.

- To a very small extent
- To a small extent
- To a moderate extent
- To a large extent
- To a very large extent
- Does not contribute
- I do not know

* D2.9 Interactive activities to include society into scientific discussions: science shops, science clubs, etc.

We refer to interaction activities responding to social concerns or interests that contribute to the social valorisation of science such as science clubs, science shops, science observatories, etc.

- To a very small extent
- To a small extent
- To a moderate extent
- To a large extent
- To a very large extent

- Does not contribute
- I do not know

Annex 5: Figures from survey data

Figure 16. Percentage of respondents stating that **open access to publications** could contribute to RP, by discipline (%)

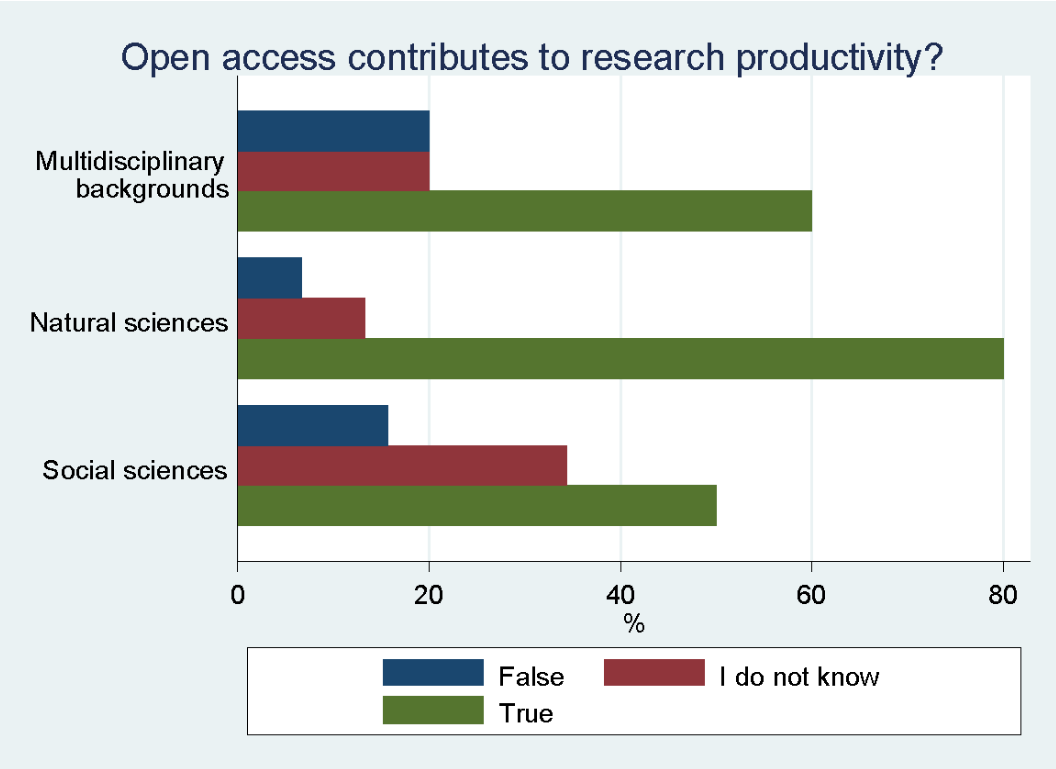


Figure 17. Percentage of respondents stating that **FAIR data principles** could contribute to RP, by discipline (%)

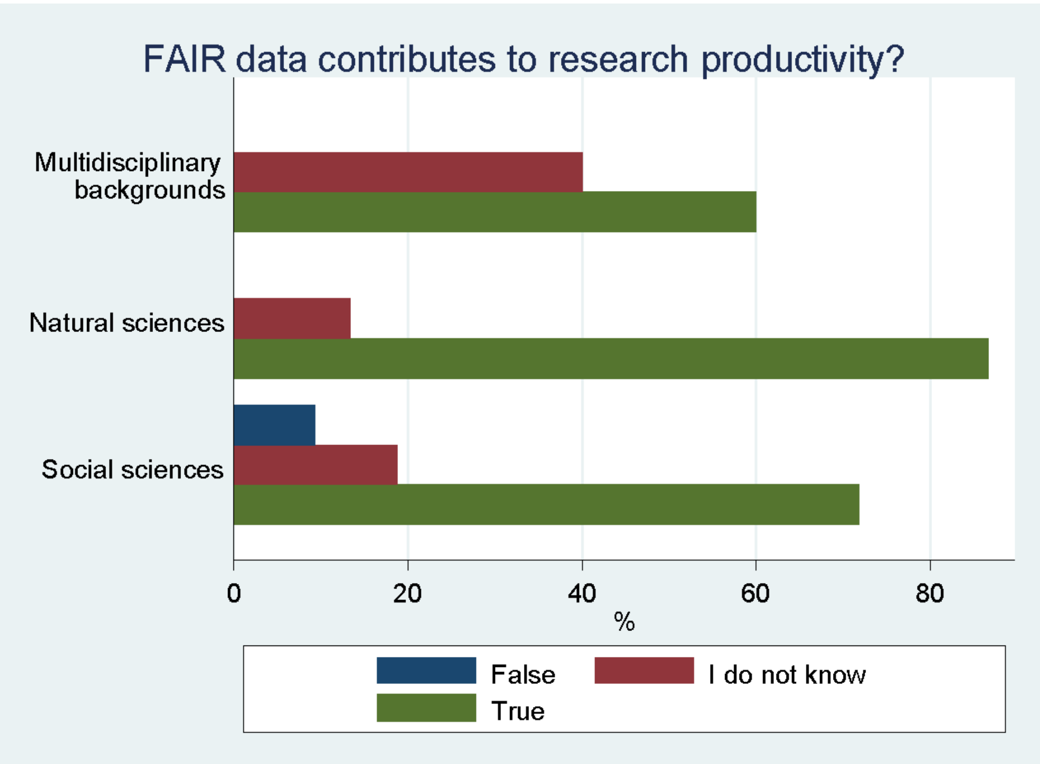


Figure 18. Percentage of respondents stating that **open licences** could contribute to RP, by discipline (%)

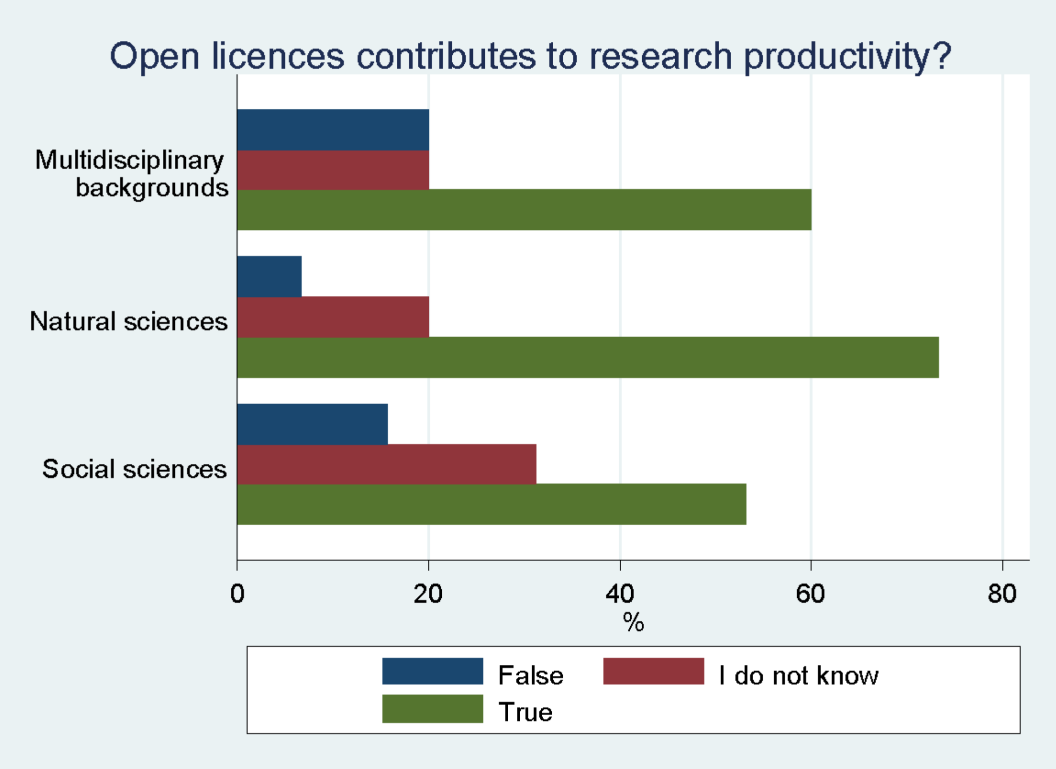


Figure 19. Percentage of respondents stating that **documenting methods and sharing** could contribute to RP, by discipline (%)

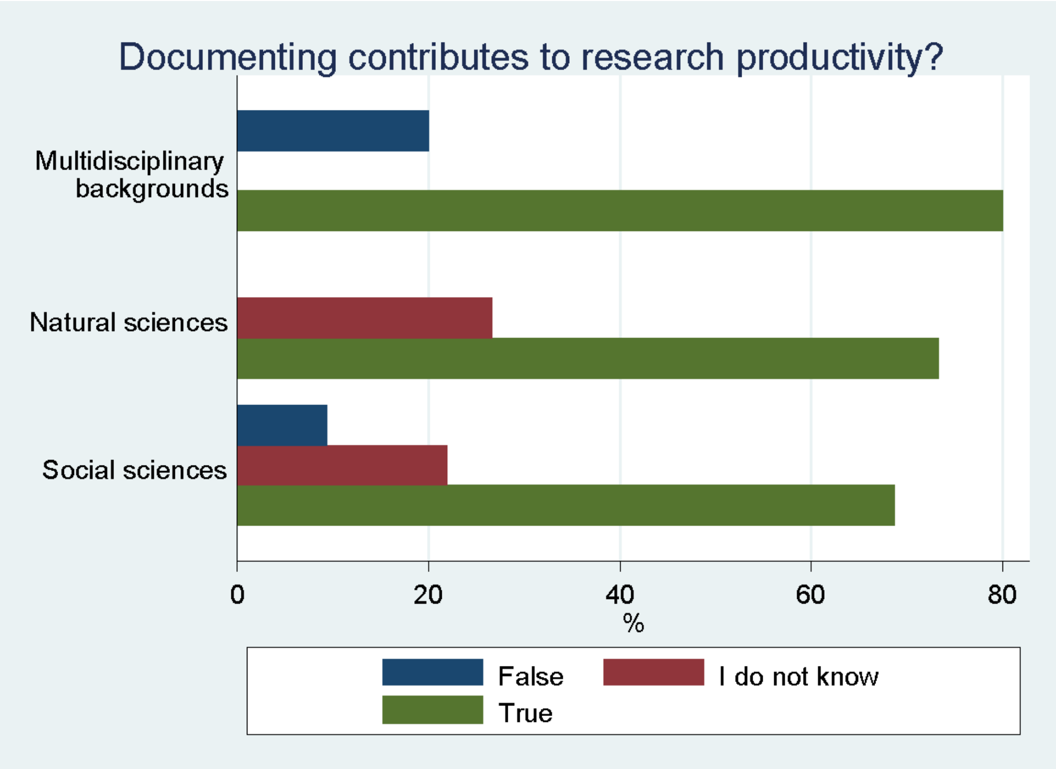


Figure 20. Percentage of respondents stating that **interdisciplinary research** could contribute to RP, by discipline (%)

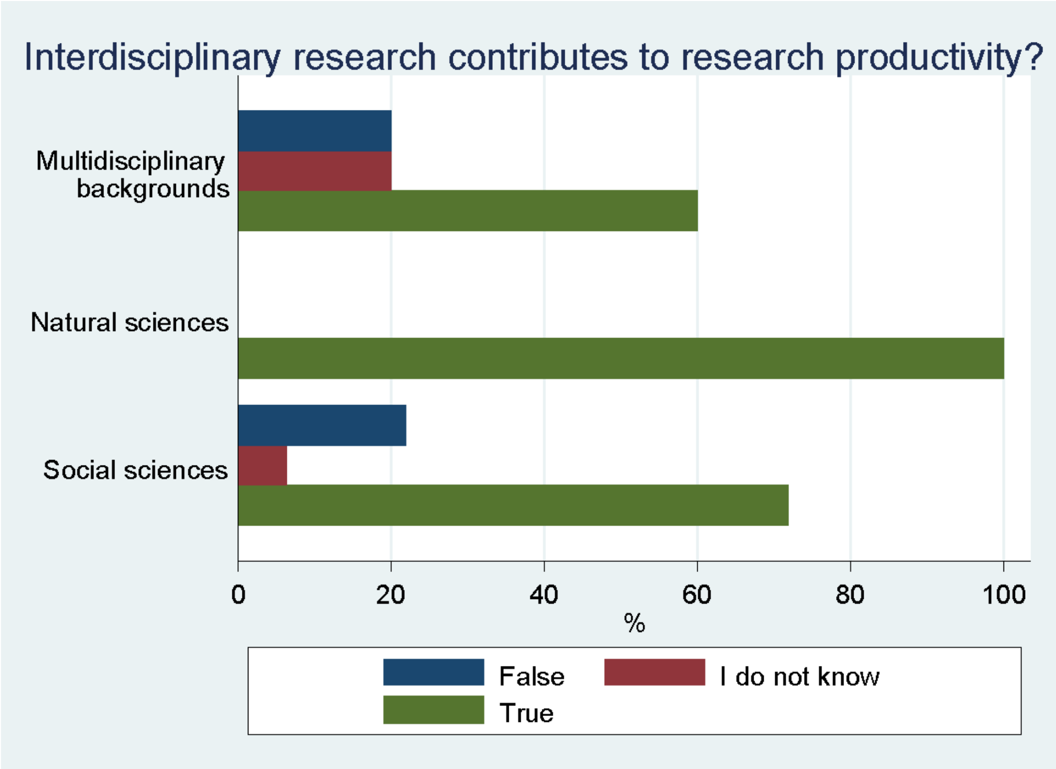


Figure 21. Percentage of respondents stating that **networked science and crowdsourcing research** could contribute to RP, by discipline (%)

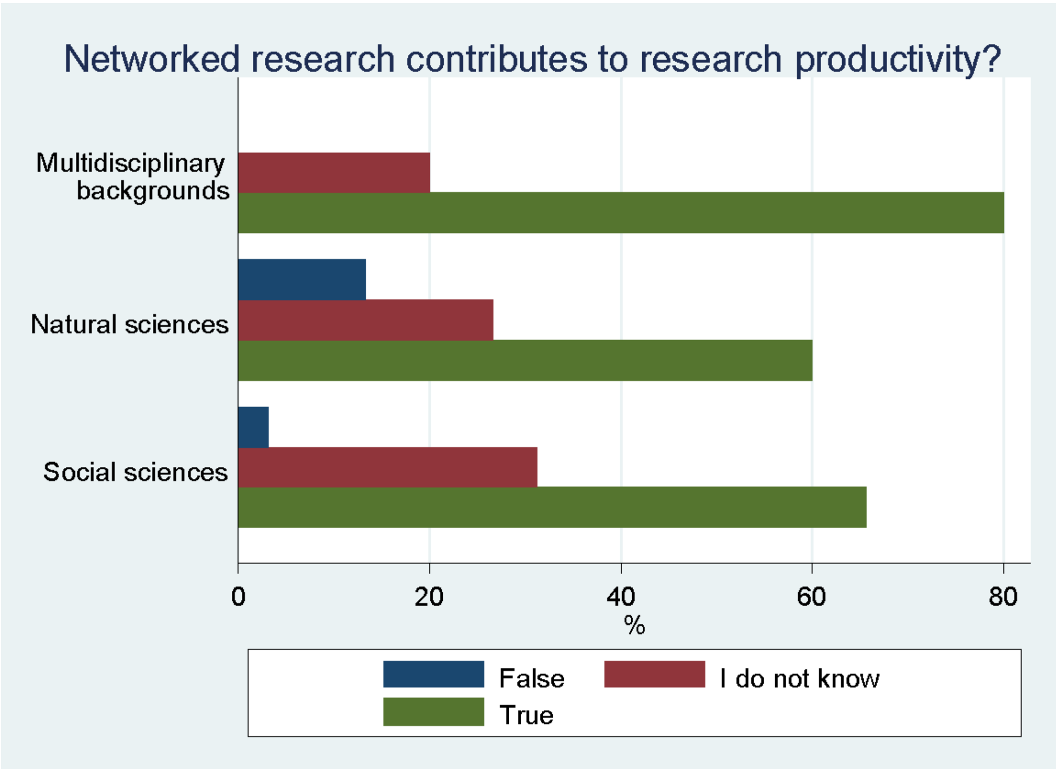


Figure 22. Percentage of respondents stating that **transdisciplinary and citizen science research** could contribute to RP, by discipline (%)

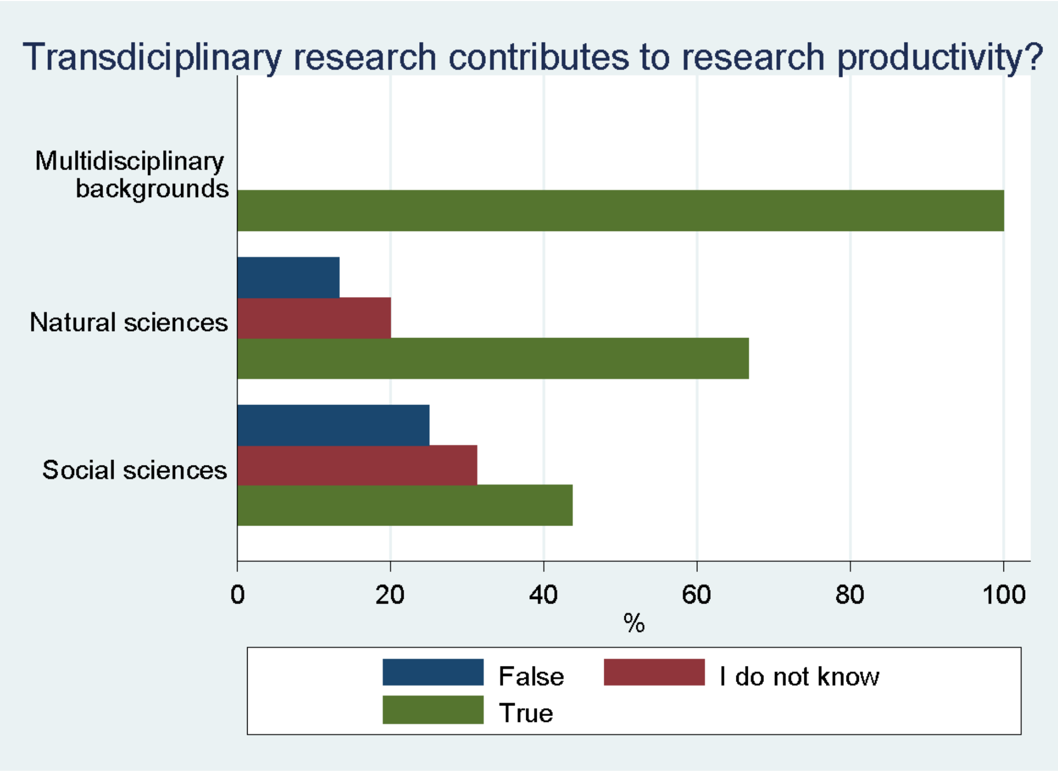


Figure 23. Percentage of respondents stating that **communication of science** could contribute to RP, by discipline (%)

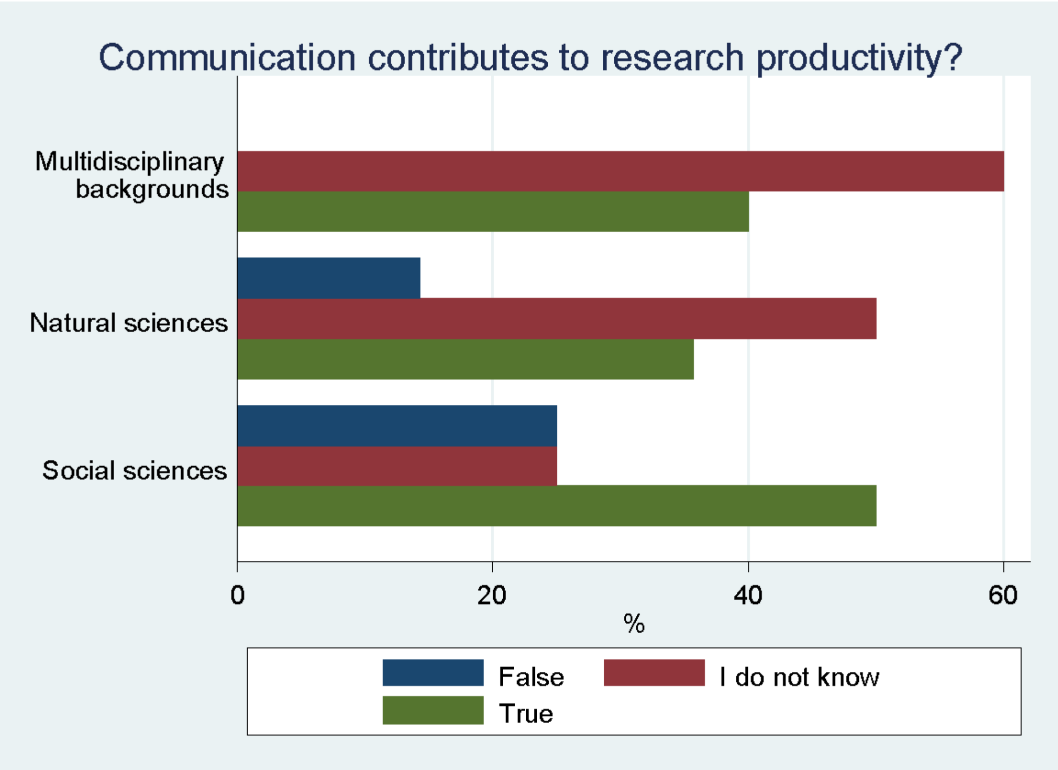


Figure 24. Percentage of respondents stating that **interaction with society** could contribute to RP, by discipline (%)

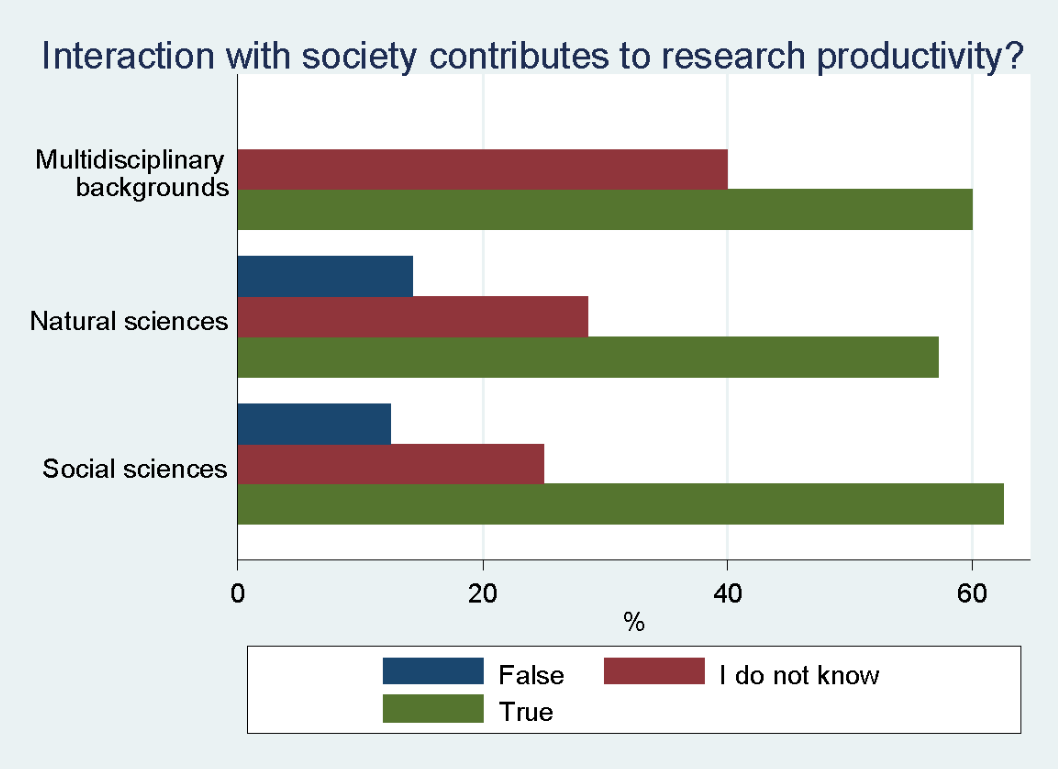


Figure 25. The extent to which **open access to publications** could contribute to societal impact, by discipline

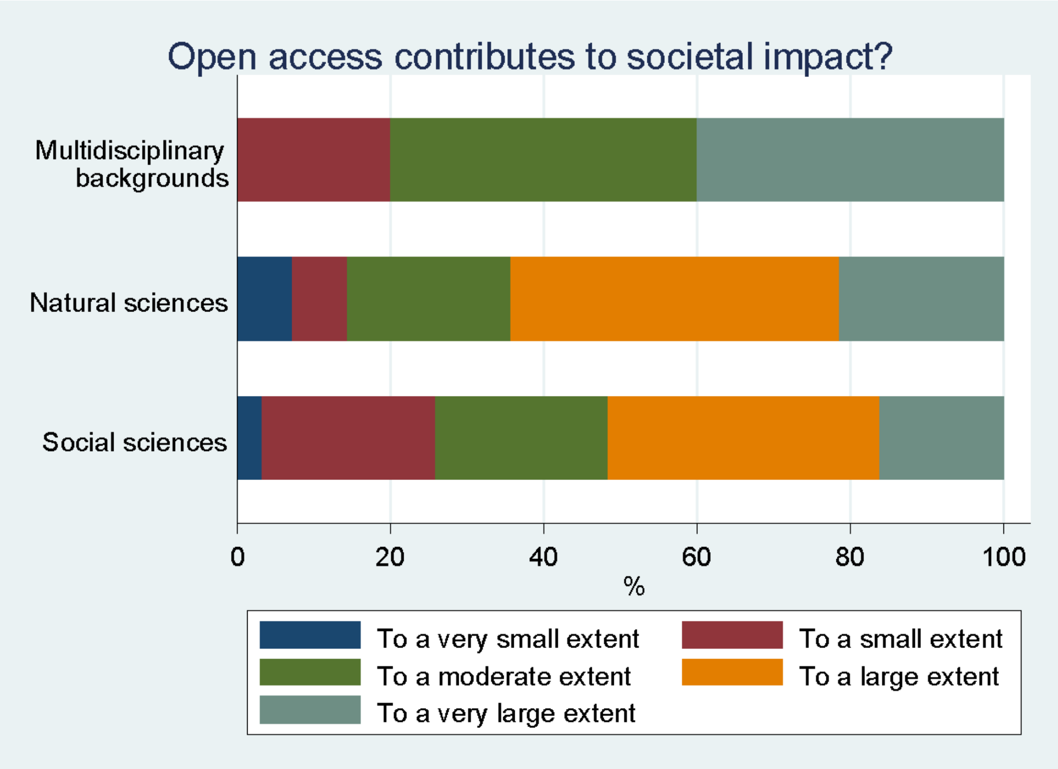


Figure 26. The extent to which **FAIR data principles** could contribute to societal impact, by discipline

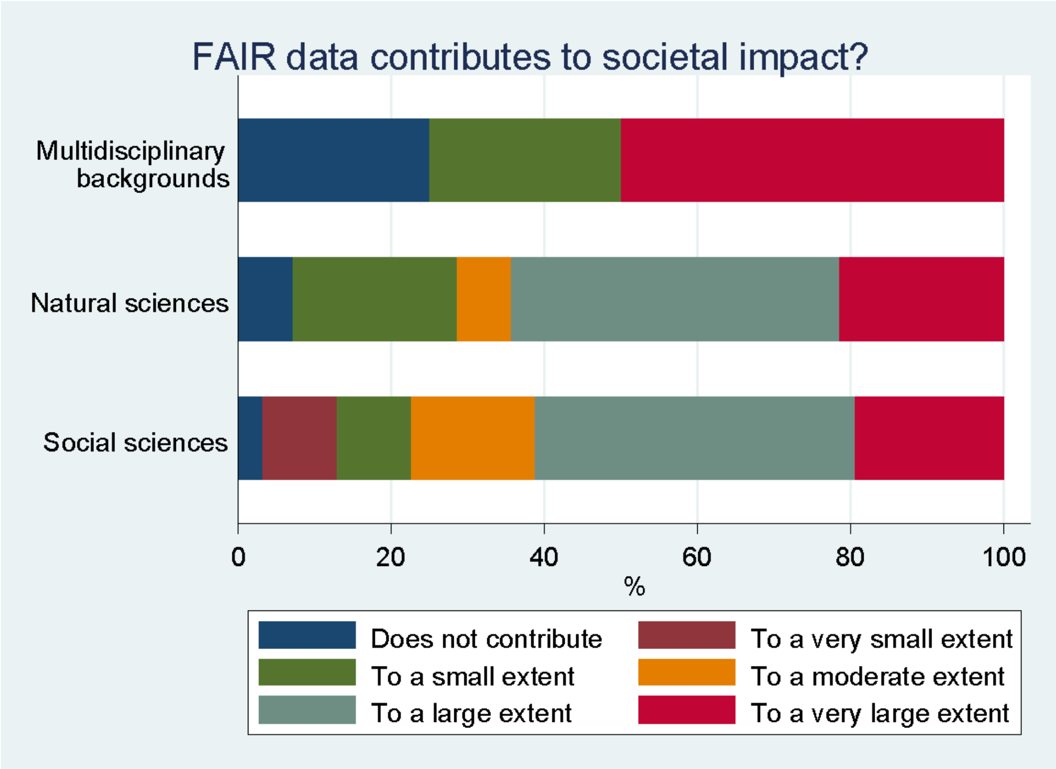


Figure 27. The extent to which **open licences** could contribute to societal impact, by discipline

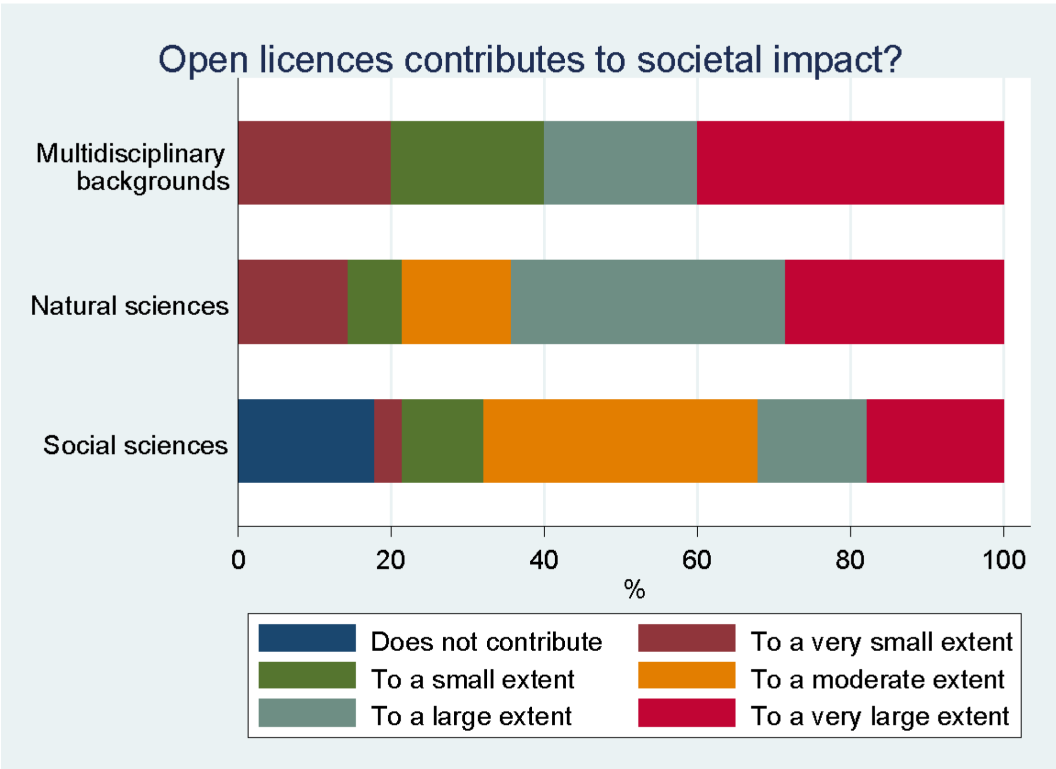


Figure 28. The extent to which **documenting and sharing** could contribute to societal impact, by discipline

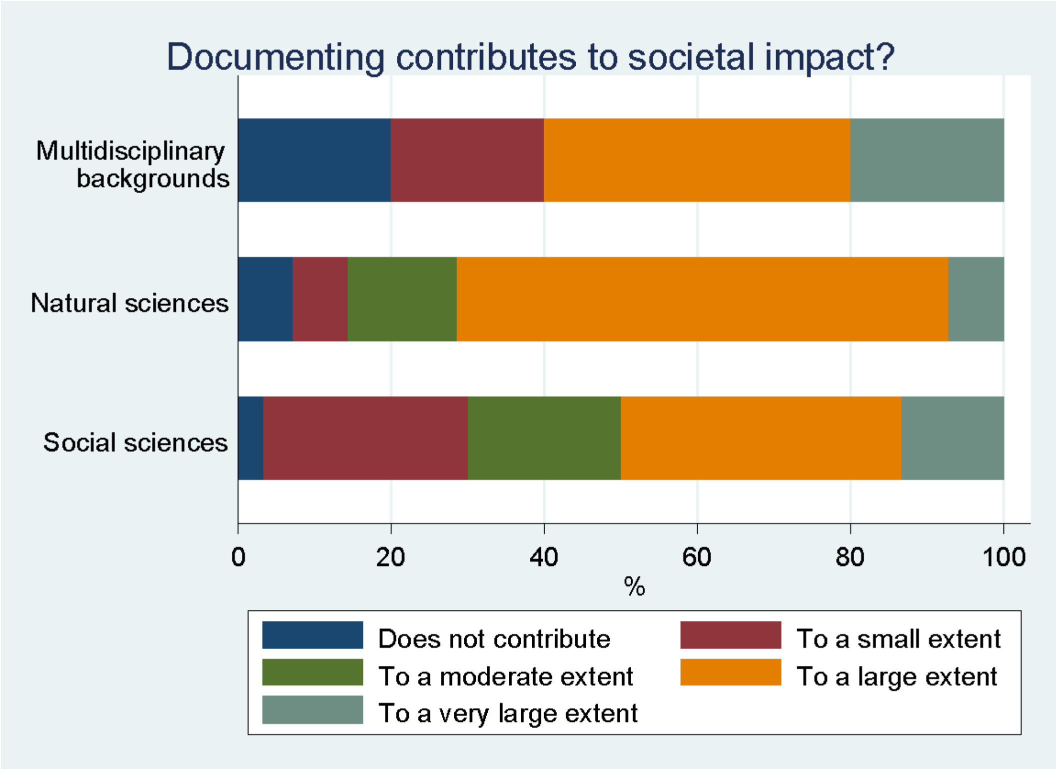


Figure 29. The extent to which **interdisciplinary research** could contribute to societal impact, by discipline

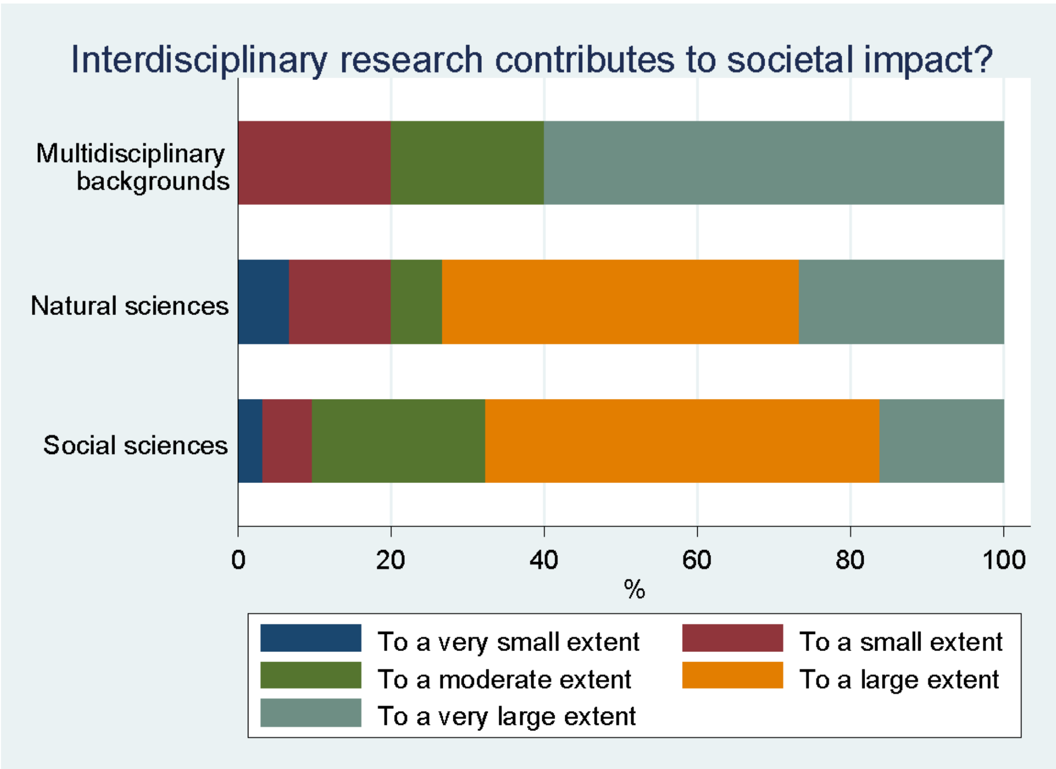


Figure 30. The extent to which **networked science and crowdsourcing science** could contribute to societal impact, by discipline

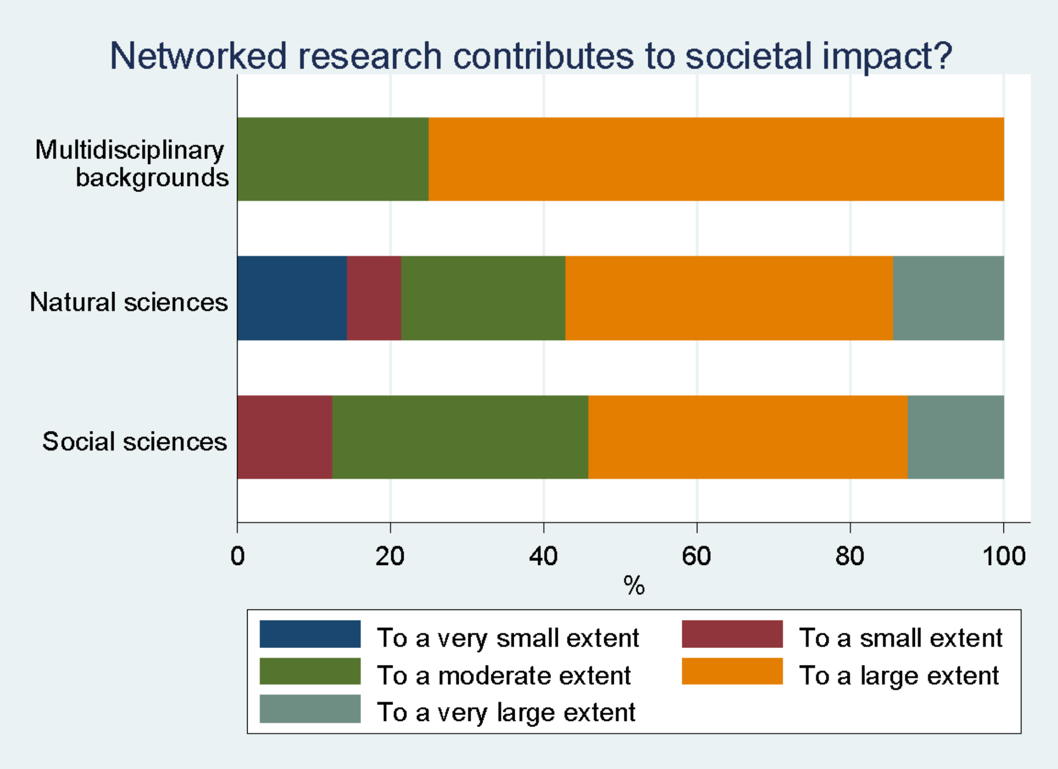


Figure 31. The extent to which **transdisciplinary research and citizen science** could contribute to societal impact, by discipline

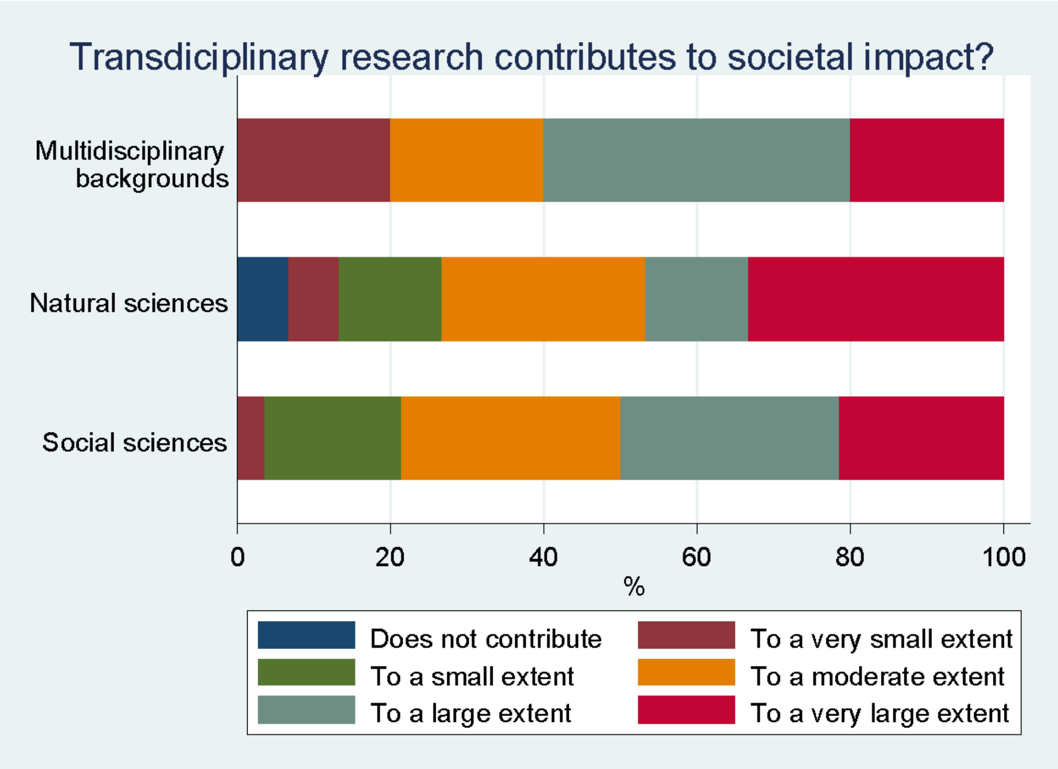


Figure 32. The extent to which **communication of science** could contribute to societal impact, by discipline

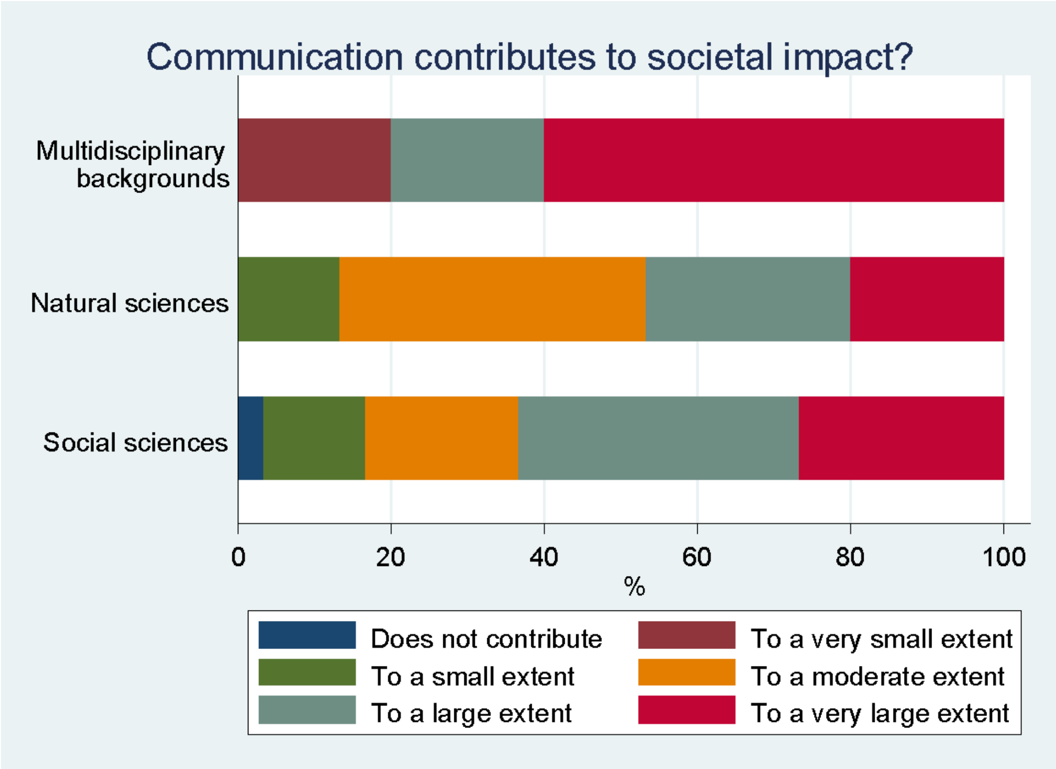
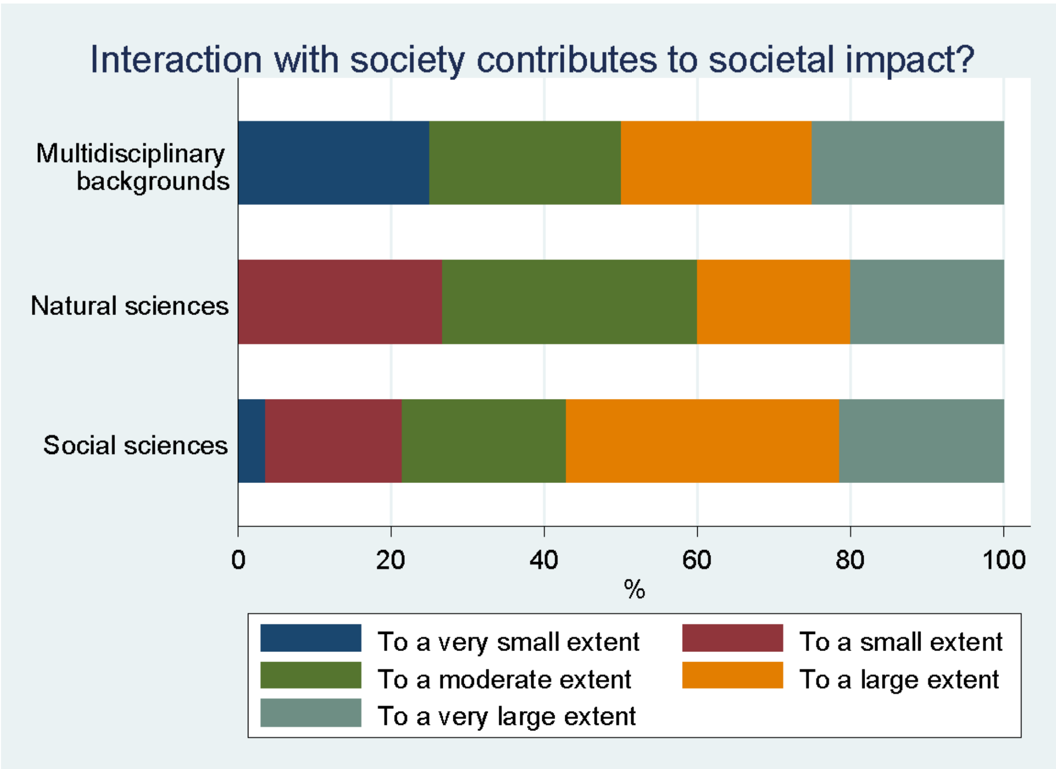


Figure 33. The extent to which **interaction with society** could contribute to societal impact, by discipline



Annex 6: Final workshop

A6.1. Exploratory interviews on selected technologies

In preparation for the plenary workshop, we conducted a number of exploratory interviews to discuss perceptions on the decline of RP in three sectors that were less covered by the sampled studies: (i) microchips, (ii) agriculture and (iii) biofuels. Interviews were held with the following experts:

- Julian Alstron (University of California, Davis)
- Ylwa Alwarsdotter (SEKAB Biofuels & Chemicals)
- Thomas Brück (Technology University of Munich)
- Johannes Kabisch (Norwegian University of Science and Technology)
- Denise Kera (Weizenbaum Institute, Tel Aviv University)
- Pantelis Koutroumpis (University of Oxford)
- Arnold Tukker (Leiden University).

In our selected sample of the literature, microchips and agriculture were discussed by Bloom et al. (2020), while biofuels were discussed by Arnold et al. (2019). Research in these sectors may have strong economic and societal impacts, for example in relation to the current shortage of microchips and the transition to sustainable mobility (biofuels; see, for example, European Commission (n.d.)). These sectors are also relevant to OS, as, for example, in the case of the long history of OS hardware and software. Finally, the three sectors provide sufficient focus to identify specific practices of open or closed knowledge that may hinder or stimulate RP.

Findings from the three sectors yielded noticeably different results. This suggests a sector- and/or technology-specific approaches to increasing RP, as also emerged from the literature review, survey and workshop discussion.

The main findings from the open interviews are described below. These are based on the direct reporting of the interview, minimising as much as possible our own interpretation (thus they reflect the views of the respondents, not our own reflections).

A6.2. Main observations from microchips

Based on the metric ‘transistor counts’, Bloom et al. (2020) find a significant decline in RP for microchips. That means that if the famous Moore’s law still holds – regarded as a big if – this is largely due to the increasing research inputs that the industry invested. While the decline is hard to oversee, the increase in inputs may actually relate to unmeasured publicly funded research inputs at the onset of this process (Mazzucato, 2021). However, these effects (i.e. the hidden public investments) have dissipated since then.

In the area of microchips, a constant stream of ideas emerge every year, fuelled by increasing research inputs, as much as Moore's law suggests ([19]). However, the increase cannot be solely attributed to the continuous introduction of new ideas; the industry itself has also grown and expanded considerably.

The technology domain of microchips is quite broad and covers an increasing range of applications and product specifications. As the world becomes more digital, microchips need to be embedded in more products with an increasing density. The first key 'idea' from this industry in the past 5 years is the departure from solutions based on software that uses mainstream computer chips towards a market where firms develop their own products or use speciality microchips (rather than generic chips that can be used in a wider range of products). This is important, as a few years ago this was an option that very few firms followed (owing to high upfront costs and a clearly uncompetitive market). We can see this trend not just from the digital giants but from others, including automakers. The second big idea is linked to the rise of machine learning applications, first as a test bed for the capabilities of traditional processors, then the shift towards graphics processing units and more recently the use of machine learning software to design microchips. This 'dematerialisation' is an example of a radical move between lines of research, which may boost the macroproductivity of the research system (i.e. boost RP; see Section A6.3).

In terms of industry structure and collaborations, the picture is pretty common across industries with increasing concentration for most of the past decade, more mergers and acquisitions deals in the past year and some reasonably optimistic signs from the departure of all Intel chips. Manufacturing seems to require that industry verticals ([20]) are well aligned for large firms, if not entirely controlled.

In the manufacturing of chips, Europe has little room to manoeuvre, as it is highly dependent upon foreign manufacturers and IP owners. In quantum computing Europe may still be able to 'leapfrog' but, due to (bad) decisions in the past, European producers cannot compete in microchips any more (see, for instance, Poitiers and Weil (2021)). In addition, research cannot happen without manufacturing. If Europe wants to have tighter control on this industry, improving RP is not the only factor that needs to be considered. Geopolitics should also be considered. Still, RP is often affected by the 'moats' that firms create to appropriate their exclusivity from their innovations. According to some respondents, one way to improve productivity would be to select some general interest

([19]) By 'ideas', the respondents probably mean novel hypotheses that have already been made actionable. That is, the ideas have given rise to new approaches (strands in science and engineering) that have already resulted in improved products (prototypes) and/or services (patterns of behaviour).

([20]) An industry vertical (also known as 'vertical market') is a group of companies that focus on a shared niche or specialised market spanning multiple industries. Thus, it has a more specific scope than industries. See, for instance, MIT Sloan School of Management (2021).

patents and open them up in a way that does not affect the short-term gains of the intellectual property owners. This could very well result in hybrid open/closed hardware platforms. One person does not need to own every piece of the component.

A6.3. Main observations from agriculture

It is hard to measure (scientific) ideas, and it is hard to directly measure a reasonable metric of scientific output. Instead, we look at the **consequences of research** on things that we can measure (e.g. crop varietal improvement innovations).

From metastudies we find that return on investment in agricultural research (i.e. 'how many dollars of social benefit do you get from funding?') has not declined over the years. Yield has been stable even though funding is decreasing.

Funding has declined partly because a lot of resources have been spent on **administering the resources** (including infighting in relation to government funding). In this respect, there is also a trade-off between competitive and continuous grants. Competitive programmes have many more rules about the structure of projects; many different disciplines and many (different types of) stakeholders need to be involved. That all chips away at the potential of the work. Meanwhile, a lot of money is spent on research projects that do not have a clear path to measurable benefits.

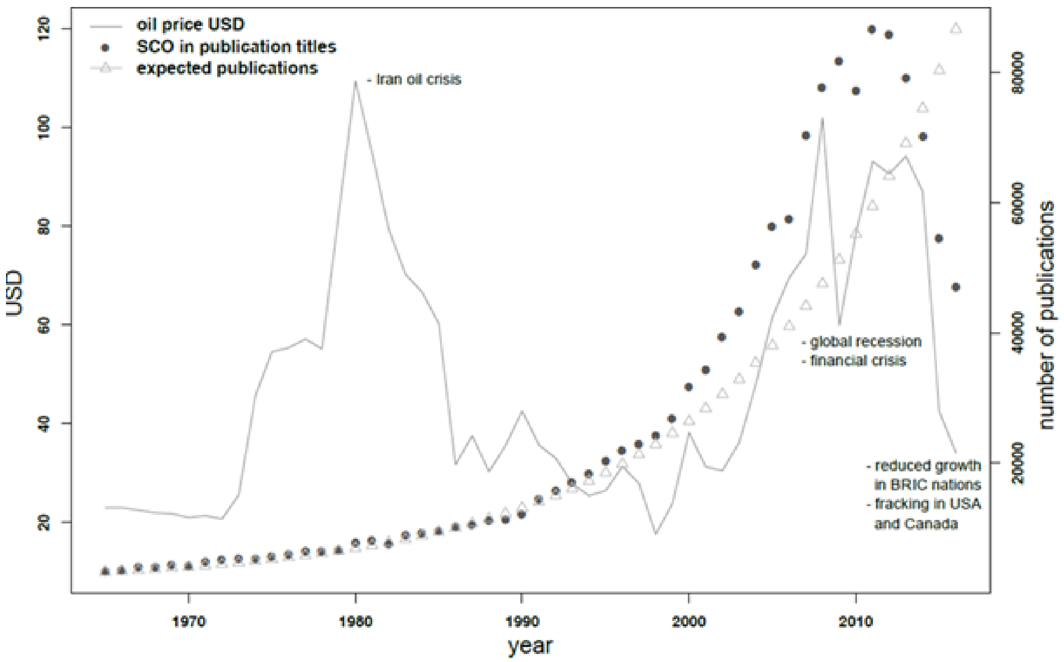
With special reference to OS, we must realise that at an individual level science is very competitive. Researchers need to publish high-level papers at a young age. Therefore, they need to protect their data. In addition, other problems such as Big Tech and the structure of intellectual property will not be solved by OS. In this respect, OS is naive. However, there are pragmatic solutions such as in astronomy. Here, little money is from private firms (although this is rapidly changing) and data management is shared. Researchers can still protect their data but only for 1 year. After that, everyone can use it.

A6.4. Main observations from biofuels

In order to translate (basic) research into societal applications, long-term commitment is needed. Each subsequent step takes exponentially more time. Hence, in terms of throughput time, research is not the bottleneck.

There is a direct link between ideation and funding. This is a one-way relationship: you need funding to get ideation, not the other way around. Until recently in the field of biofuels there were more ideas than ever before. The bottleneck is in developing scientific ideas further, and this is entirely due to a lack of funding. Current research in biofuels is entirely determined by the established industry. As a result, there is a strong bias towards technologies that suit the vested interests best. Therefore, the dominant line of research is in technologies that are not optimal choices from a sustainability point of view. They are the last step in the old line of research rather than the first step towards a truly green revolution.

Figure 34. Trends in biofuels (SCO) publications.



NB: SCO refers to microbial lipids. These are highly attractive feedstocks for biodiesel production owing to their fast production rates, minimal labour requirements, independence from seasonal and climatic changes, and ease of scale-up for industrial processing. SCO, single-cell oils; BRIC, Brazil, Russia, India and China.

Source: Bruder et al. (2018).

The primary role of governments is to lead, that is to guide socioeconomic developments in new directions. This requires bold choices in terms of policymaking and regulation, and a long-term government. In the field of biofuels, the key parameter is a product that is so cheap that you can burn it. However, because of the lack of commitment of the government to fair CO_2 pricing, research in the field is refocused on high-end markets.

The respondents also made several bold statements about the importance (and the lack) of research communications. Right now research communication is completely disjointed from research funding. Most research projects funded by the European Commission are obliged to communicate with the public. However, Commission officials are provided with very little information (and they do not seem to be very involved). The respondents think this is a big missed opportunity.

A6.5. Report of the final workshop

The final workshop was held online on 21 September 2021. The agenda of the workshop is provided in Section A6.9. The workshop was organised and coordinated by Dialogic.

At the beginning of the workshop the results of the literature review and survey were presented and discussed with several experts. Six provocations were discussed in group sessions to acquire additional input from the experts. As such, the workshop served as a opportunity to gain feedback on and validate the results of the study.

The participating experts were:

- Professor Bart Van Ark (Professor of Productivity Studies, University of Manchester)
- Professor James A. Evans (Professor of Sociology, University of Chicago)
- Professor Santo Fortunato (Professor of Informatics and Computing, Indiana University Bloomington)
- Dr Konstantinos Glinos (Head of Unit for Open Science, Directorate-General for Research and Innovation (DG R & I))
- Professor Richard Gold (Professor of Intellectual Property Law, McGill University)
- Professor Alan Irwin (Professor of Organization, Copenhagen Business School)
- Professor Paul Nightingale (Professor of Strategy, University of Sussex) ([21])
- Dr Ismael Rafols (senior researcher, Centre for Science and Technology Studies, Leiden University).

Observers of the workshops were:

- Michael Arentoft (DG R & I)
- Patrick Brenier (DG R & I)
- Johannes Kabisch (Norwegian University of Science and Technology)
- Pantelis Koutroumpis (University of Oxford)
- Angelica Marino (DG R & I)
- Thomas Neidenmark (DG R & I)
- Angela Pereira (Joint Research Centre)
- René von Schomberg (DG R & I).

A6.6. Discussion of the results of the study

In the first session of the workshop the results of the study (systematic review and survey) were presented. The definition of RP used in this report, according to the innovation framework, received a number of critical comments from the experts. As this definition considers the research input in relation to (successful) outputs, experts worry that it may emphasise innovations that are not high risk or radical, and that destroy the value of earlier innovations. Increasing the amount of genuine innovations increases the amount of failures, which are not accounted as outputs in the definition based on the innovation framework.

([21]) Professor Nightingale replaced Jennifer Rubin (Chief Scientific Advisor, Home Office).

Furthermore, the extent to which output is genuinely and radically innovative may lead to much longer implementation paths, where research outputs may take decades to be implemented in industry or society. This makes the definition and discussion of RP based on innovations politically fragile, as policies to increase successful outputs may erode the extent to which outputs are truly innovative. A focus on quantity may in other words impede the quality of innovations. A focus on quantity may also disproportionately shift policy attention towards research fields with a stronger culture of increased output, away from fields that require more time for output. This reduces the macroeffectiveness of the R & I system. While the COVID-19 crisis demonstrated that innovations can be implemented with impressive speed, with vaccines developed in a matter of months, these vaccines depended on mRNA research that had been conducted for decades before.

A6.7. Discussion of provocations

In the second part of the workshop, six provocations were discussed. The first three provocations focused on RP, while the latter three provocations focused on OS.

Provocation 1

Research productivity is the ratio of research inputs to innovation outputs. Improving research productivity requires an improvement in the efficiency of the research system or funding in generating/developing innovations (not just publishing), which may be leading to socioeconomic benefits.

Experts problematised the relationship between productivity and efficiency. Particularly for research, efficient research does not automatically imply impact. As noted in the earlier discussion, radically innovative research inherently implies inefficiency, as it allows many more failures and non-linear outcomes that are hard to measure. Especially when considering the ultimate impact of research on socioeconomic benefits, these may be too distant in time and difficult to attribute to the original research to measure RP meaningfully as defined in the provocation.

Provocation 2

A decline in research productivity is found only in a few sectors. Why is there so much buzz about a general decline?

Experts noted that even if a decline in RP is not a general trend, it is still a topic worthy of scrutinization. While science at large may not be less productive per se, experts agreed that the impact of the organisation of science on productivity is problematic. One problem is that researchers are increasingly working on administrative tasks such as research proposals, justifying expenditures and moving between temporary positions. Furthermore, experts noted that in principle productivity can only decline. On the one hand, the body of knowledge to which science contributes is increasingly large and therefore increasingly difficult to innovate upon (the 'endless frontier argument') (Chu and Evans, 2021). On the other hand, when considering, for example, the impact on life expectancy there are limitations to how much life expectancy can be increased ('diminishing returns'). However, the macroproductivity of the research system may benefit from moving between radically different lines of research. For example, (hypothetically) we may experience an increase in RP in cancer research by shifting funding from chemotherapies towards understanding the causes of cancer (e.g. its relation to pollution), that is shifting funding to the prevention of cancer from the treatment of cancer.

Provocation 3

The two main factors hindering research productivity are evaluation pressure (such as a disproportionate focus on number of publications as an indicator of productivity and reliance on bibliometric impact factors) and R & D management (such as administrative burden). What are the main remedies to increase research productivity?

Experts reacted somewhat critically to this statement, noting that asking scientists about hindering factors (as done through the survey) will result in replies that benefit scientists personally (such as complaints about administrative work) rather than the system overall. However, experts did agree that the current evaluation system may introduce several factors impeding RP. As grants largely depend on previous successful work, young researchers in particular who are still on temporary contracts may conduct less high-risk research, leading to less innovative work, as their main concern is to produce successful outputs rather than learn from failures. As such, there is a risk that the competitive system does not select the best candidates to develop and conduct innovative (and high-risk) research. In relation to this, researchers tend not to publish negative findings, which increases the risk of redundant, unsuccessful work (if failures are not shared). Furthermore, selection is conducted before research is funded. It is then difficult to assess the impact that research may have, leading to exaggerated promises of impact. Research projects can moreover still take different routes after receiving a grant. Overall, experts questioned whether or not the current evaluation system is aimed at benefiting society, as societal stakeholders are seldom in close contact with research proposals. As such, it is noted that interdisciplinarity is hard to encourage in the current system.

Provocations 4 and 5

Open science increases efficiency by facilitating the circulation of innovative ideas, reducing duplication, and by reducing the cost of collecting and using data.

Open science sounds nice in theory but may be naive in practice: science is too competitive (e.g. owing to patents, evaluation pressures and mentality) to share ideas. In addition, documenting and sharing is costly and not always possible (data confidentiality).

These two provocations were discussed in tandem.

Experts noted that these two provocations together show that OS may have downsides at individual level, while still being beneficial to the system as a whole. One expert compared this to classical market failure, where individual incentives clash with system requirements. As such, this is a case where governmental intervention is needed to align individual practices with system benefits. However, to balance individual and system requirements, it may be advisable not to demand OS practices from every researcher at all times, but require them to be flexible in the implementation of OS principles as needed.

A benefit of OS is that it may prevent erroneous or fraudulent behaviour, as research designs and data are shared. This may increase the replicability of research, positively affecting RP.

Factors related to OS practices that may instead hinder RP at individual level include that increased access to publications and data increases researchers' workloads to assess the increasing body of knowledge, not only from their own fields of research but also from other fields to which they gain access. Another downside may be that researchers may become dependent on existing data to test hypotheses, rather than creating their own data, which may decrease productivity overall. Finally, experts agreed that OS decreases productivity in the short term, as substantial investments are needed to develop and maintain research (data) infrastructures. As such, increased input in the system is required for factors that do not directly lead to outputs in the short term.

Provocation 6

Opening research to different players increases the relevance of the research question, and broadens the research frame, which in turn increases the productivity of scientists.

Experts noted that OS should not be defined too narrowly, moving beyond open access and open data to indeed include engagement with societal actors (such as industry, policymakers and the public). Experts noted that increasing the transparency of research will eventually increase the trust of the public in science and scientific results. However, experts worried that brokering and translating research to societal actors may impede RP, as more activities are undertaken that do not directly lead to increased output. Furthermore, young researchers may not benefit individually from engaging in such activities to move ahead in their careers.

A6.8. Discussion of policy options

In the final session four provoking policy options to improve RP were presented. The four options were as follows.

1. **More resources for R & D.** Given the potential diminishing returns to R & D (due to what we call the 'fast-expanding endless frontier'), governments can only maintain current levels of innovation through increasingly large injections of resources. However, more money is not necessarily better; sometimes the money just needs to be better spent. There is clear evidence that the social returns to science are huge – but funders should be careful where they put their money.

2. **Changes in research funding priorities.** Most of the research in the world is done on issues unrelated to the major societal challenges (e.g. SDGs). Changes in the design of research funding policies towards the most impelling societal challenges may help to generate innovations/ideas that are more relevant to society and increase RP. However, there should still be room for researchers to take risks and pursue different avenues of research.

3. **Changes in research evaluation practices.** Research evaluation has become routine and often relies on scientific output metrics. Reliance on 'publish or perish' culture may incentivize incremental changes rather than breakthroughs. Is it time for funders to do more research on themselves to understand how funding should be designed and organised?

4. **OS policies.** OS may improve RP as a result of its effects on research efficiency (avoiding duplication, and increasing use of knowledge stocks and collective intelligence); research reliability (owing to increased transparency and reproducibility) and research responsiveness to social needs (diversity and plurality in scientific participation could improve problem identification, and increased trust and visibility may promote policy dialogue).

Experts noted that none of the policy options is sufficient alone, and that they are not exclusive. On the contrary, these options are strongly related. Scenario 1 (increasing resources) may be the most desired scenario by researchers, but needs to be combined with scenarios 2 (changing funding priorities) and 3 (changing evaluation practices) to be effective. Furthermore, Scenario 2 may involve diversifying priorities not only horizontally across more topics, but also vertically by diversifying across actors within existing topics. Finally, experts warned to be somewhat careful with scenario 2; research priorities should not be set too narrow, but room should be left for researchers to take risks and pursue different avenues of research.

Furthermore, experts agreed that the four policy options were too strongly top-down, with bottom-up practices to improve RP lacking. To this end, a fifth scenario 'changing the research system' was proposed, aimed at not only researchers as individuals but also research institutes as employers of researchers. In relation to scenario 3 ('changing evaluation practices'), experts noted this concerns not only funders but also institutions who evaluate personnel. Moreover, the interaction between research and teaching is a topic of concern to RP that is mainly discussed at institutional level. Finally, there is the question of how research institutes may be incentivised to adopt or facilitate increasingly high-risk research behaviour. Without this fifth scenario, it may not even be possible to successfully pursue scenarios 2, 3 and 4; when research institutes do not desire changes in the research system, policy interventions may not prove successful.

A6.9. Programme of the final workshop

21 September 2021 (15.00–18.30 CET)

14.45–15.00: Drop-in (participants; 15 minutes; online coffee corner)

15.00–15.05: Introduction from the European Commission (Kostas Glinos; 5 minutes)

15.05–15.15: Introduction participants (Robbin te Velde; 10 minutes)

15.15–15.35: Presentation of the conceptual framework and results of the study (Tommaso Ciarli; 20 minutes)

15.35–16.00: Plenary discussion (experts; 25 minutes)

16.00–16.15: Short break (15 minutes)

16.15–16.45: Discussion of first three provocations (on RP) (experts; 30 minutes; discussion in two parallel breakout rooms):

1. *Research productivity is the relation between research inputs (e.g. funding, human capital, etc.) and innovation outputs (e.g. technologies, patents, ideas, solutions to problems, etc.). Improving research productivity implies improving the efficiency of the research system/funding in generating/developing innovations (not just publishing), which may be leading to socioeconomic benefits*
2. *A decline in research productivity is found only in relation to a few sectors. Why is there so much buzz about a general decline?*
3. *The main two factors hindering research productivity are evaluation pressure (such as a disproportionate focus on number of publications as an indicator of productivity and reliance on bibliometric impact factors) and R & D management*

(such as administrative burden)'. What are the main remedies to increase research productivity?

16.45–16.50: Switch between breakout rooms (5 minutes)

16.50–17.20: Discussion of last three provocations (on OS) (experts; 30 minutes; discussion in two parallel break-out rooms)

4. *Open science increases efficiency by facilitating circulation of innovative ideas, reducing duplication and by reducing the cost of collecting and using data*
5. *Open science sounds nice in theory but might be naïve in practice: science is too competitive (patents, evaluation pressures, mentality) to share ideas. Also, documenting and sharing is costly and not always possible (data confidentiality).*
6. *Opening research to different players increases the relevance of the research question, it broadens the research frame, which in the end increases the productivity of scientists.*

17.15–17.30: short break (15 minutes)

17.30–17.40: Overall summary of discussions (Robbin te Velde; 10 minutes)

17.40–17.50: Introduction to policy options to improve research productivity (Diego Chavarro; 10 minutes)

17.50–18.15: Discussion of the most effective policy options (experts; 25 minutes)

18.15–18.20: Summary of the results from policy options (Robbin te Velde; 5 minutes)

18.20–18.30: Closing the workshop (René van Schomberg; 10 minutes)

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Study on factors impeding the productivity of research and the prospects for open science policies to improve the ability of the research and innovation system to transform financial investments in research into valuable outputs such as breakthrough innovations

This report aims to review evidence on three related lines of enquiry at the core of the current debates on research policy and practice: (i) factors that can hinder the productivity of research; (ii) prospects for open science practices to improve research productivity; and (iii) the ability of research and innovation systems to transform financial investments in research into valuable outputs and societal outcomes. We combine evidence on these topics to devise areas of action and policy guidelines to transform research and innovation systems to make them more productive and impactful. The following questions guided our research.

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