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Towards responsible science and technology: How nanotechnology research and development is shaping risk governance practices in Australia

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Incorporating perspectives of multiple stakeholders concerning the appropriate balance of risks and benefits of new and potentially disruptive technologies is thought to be a way of enhancing the societal relevance and positive impacts of those technologies. A risk governance approach can be instrumental in achieving balance among diverse stakeholders, as it enables decision-making processes informed by multiple dimensions of risk. This paper applies a risk governance approach to retrospectively examine the development of nanotechnology research and development (R&D) in Australia to identify how risk governance is reflected in the practices of a range of stakeholders. We identify ten risk-related challenges specific to nanotechnology R&D based on a review of the international literature, which provided the foundation for documenting how those working in the Australian nanotechnology sector responded to these global risk-related challenges. This case study research draws on a range of sources including literature review, semi-structured interviews, and a combination of qualitative and quantitative approaches for data analysis to identify key themes and generate visualisations of the interconnections that exist between risk governance practices. The ability to visualise these interconnections from the qualitative data is a key contribution of this research. Our findings show how the qualitative insights and professional experiences of nanotechnologists provide evidence of how risk governance approaches have been operationalised in the Australian nanotechnology R&D sector. The findings generate three important insights. First, the risk research undertaken by Australian nanotechnologists is interdisciplinary and involves multiple stakeholders from various disciplines and sectors. Unlike traditional risk governance approaches, our findings document efforts to assess, not only physical risks, but also social and ethical risks. Second, nanotechnology risk governance is a non-linear process and practices undertaken to address specific challenges occurred concurrently with and contributed to addressing other challenges. Third, our findings indicate that applying a risk governance approach enables greater intersection and collaboration, potentially bridging any disconnect between scientists, policymakers, and the public to realise transdisciplinary outcomes. This research highlights opportunities for developing systematic methodologies to enable more robust risk governance of other new and emerging technologies.

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Introduction

The increasingly rapid pace of innovation in technology development requires that decision-makers must also be increasingly responsive in determining the appropriate governance of a range of new technologies in order to balance the associated risks and benefits of technology adoption (Quirion et al., 2016). Failure to make these assessments accurately has consequences for how effectively these technologies can deliver benefits to society. For new and potentially disruptive technologies, achieving the balance between benefits and risks in a way that is inclusive of perspectives of multiple end-users and stakeholders is thought to increase the societal relevance and impact of technology R&D (Lubchenco, 1998; Toumey, 2011).

To understand the risk profile of potentially disruptive technologies, a risk governance approach can be instrumental for integrating both physical and social risks (Renn and Roco, 2006a, 2006b). Risk governance is an approach that informs decision-making processes that incorporate, or are at least informed by, multiple dimensions of risk (Renn, 2008). In this paper, we apply a risk governance approach to examine the trajectory of nanotechnology research and development (R&D) in Australia over the last two decades so as to identify how risk governance practices have been developed in this context. Multiple aspects of nanotechnology R&D and its governance have been extensively documented in the international literature (Fisher et al., 2006; Fisher and Maricle, 2015; Krabbenborg, 2020; Swierstra and Rip, 2007). However, the benefit of retrospectively examining the risk governance of nanotechnology R&D in Australia provides a unique opportunity to not only reflect on key international developments but to document the experience and practice of Australian nanotechnologists. This identifies how risk governance approaches have developed in the context of Australian nanotechnology R&D and allows these risk governance approaches to potentially inform how risk governance might be applied to other emerging technologies.

While risk governance theories are well established in the scholarly literature and numerous risk governance case studies exist (Read et al., 2016; van der Vegt, 2018), this case study of Australian nanotechnology R&D makes two clear contributions to risk governance scholarship. First, we identify and describe ten risk-related challenges specific to nanotechnology R&D based on a review of the international literature. This is the first time these ten challenges associated with nanotechnology R&D have been brought together to inform a risk governance assessment. We then locate our assessment in the context of Australia by identifying and documenting various risk governance practices employed by Australian nanotechnologists (including scientists, regulators, engineers, and academic researchers) in response to those global challenges and describe how these practices have contributed to the development of the sector.

Second, we use these findings to show how risk governance has been operationalised in the context of the Australian nanotechnology R&D sector, which includes examining contextual influences such as research funding, regulation, and policy processes. The central idea of risk governance in this research is that decisions about the risks and benefits of technologies arise from non-linear and multi-actor processes comprised of interconnected components (Malakar and Lacey, 2020; Renn, 2008), particularly in response to more complex and uncertain types of risk. In this research, we use the five components of a risk governance framework to examine and visualise how such interconnections are expressed in a more systemic way (i.e. non-linear in this research denotes that risk tends not to be identified, experienced, or managed in pre-identified and sequential steps but occurs simultaneously through a range of intersecting processes).

While non-linear and multi-actor processes are often described in risk governance theories (Renn, 2008) and qualitative narratives (Linkov et al., 2018), our research further contributes to the risk governance scholarship by undertaking a qualitative analysis and then quantitatively visualising the strength of the interconnections between risk governance practices related to Australian nanotechnology R&D. This analysis is undertaken to demonstrate how the critical components of a risk governance framework, which involve multiple actors, interact to reinforce and strengthen an overall risk governance approach. This research examines the roles of scientists and policymakers (Lacey et al., 2018; Obermeister, 2020), and identifies where the public also contributes to shaping the risk governance of nanotechnology R&D (Albert, 2021; Haerlin and Parr, 1999). The aim of the analysis presented in this research is not to evaluate the effectiveness of these nanotechnology risk governance practices themselves but to demonstrate the range and breadth of these practices among multiple stakeholders and how they have shaped the interconnected nature of risk governance of nanotechnology R&D in Australia.

Nanotechnology R&D: International and Australian context

Globally, the investment in nanotechnology increased from the early 2000s with the United States and Europe among the top investors (Roco et al., 2011). In the United States, the *21st Century Nanotechnology Research and Development Act* was a critical milestone in the R&D of nanotechnology (US Congress, 2003), and led to the establishment of the National Nanotechnology Initiative (NNI) (Hulla et al., 2015). In its strategic plan developed in 2014, the NNI envisioned a nanotechnology-led revolution in technology and industry to benefit society (Kaiser et al., 2014). Similarly in Europe, nanotechnology R&D was initially guided by the *Towards a European strategy for nanotechnology* report published in 2004 (European Commission, 2004), which laid out key strategies for funding and institutional arrangements. However, in 2020 European strategy continues to identify nanotechnology as central to becoming a highly competitive knowledge-based global economy (European Commission, 2020). In Australia, nanotechnology R&D emerged around the same time as it did globally. Since this time, the aim for Australian nanotechnology R&D has been to deliver globally competitive research and advanced applications across various sectors including energy, health, transport, and communication among others (Australian Academy of Science, 2009).

Alongside the range of potential benefits, the advent of nanotechnology R&D around the world also prompted concerns relating to potential risks to human health (Nel et al., 2006), the environment (Nowack and Bucheli, 2007), and society (Fisher, 2005; Pidgeon et al., 2011). Various initiatives were undertaken to better understand the associated risks and societal concerns. For example, the Royal Society and Royal Academy of Engineers conducted a study examining the opportunities and uncertainties of nanotechnologies (Royal Society and Royal Academy of Engineers, 2004). A similar study was conducted for the members and committees of Congress in the United States (Sargent, 2008). The European nanotechnology strategy of 2004 (European Commission, 2004) and the nanotechnology Act of the United States (US Congress, 2003) emphasised the need to address societal concerns around nanotechnology. In Australia, the commitment to expanding nanotechnology R&D also met with concerns about potential risks, particularly between 2005 and 2010, which triggered a series of responses by different Australian institutions. The Australian context of nanotechnology R&D is explained in detail in Supplementary Note 1. By documenting these developments and key milestones in Australian nanotechnology R&D along with the nature of societal concerns and the policy and risk responses that were implemented, this paper examines the geo-political context in which Australian risk governance practices in nanotechnology R&D were developed.

A systematic comparison between the Australian and global nanotechnology sectors is beyond the scope of this paper. However, we identified some similarities and differences when situating Australian nanotechnology R&D within the global context. For example, the motivations for pursuing nanotechnology R&D were similar, and this was largely to advance manufacturing, economic development, and deliver benefit to society. The importance of embedding social aspects into the R&D process was also recognised by the Australian and international nanotechnology sectors. For example, the Australian nanotechnology strategy underlined the need to build public confidence in order to attain broader social acceptance of nanotechnology (Australian Academy of Science, 2012, p. 13). Similar to Europe, the adequacy of regulatory frameworks was examined in Australia (Bowman and Hodge, 2006b; Ludlow, 2008). When comparing the findings of the Australian report with the European Commission's review of the regulatory aspects of nanomaterials (European Commission, 2008), both provide similar conclusions indicating that existing legislation was deemed to adequately address safety concerns. However, in Australia, some regulatory gaps were identified that were addressed through collaboration among multiple regulatory agencies and government departments (Ludlow et al., 2007). In terms of policy development, Australia appears to have progressed a little more slowly than its global counterparts, given that the United States developed its Nanotechnology Act in 2003 and Europe developed its nanotechnology strategy in 2004. Although there were early discussions about developing a nanotechnology strategy in Australia in 2006 (National Nanotechnology Strategy Taskforce, 2006), the strategy was finally published in 2012. Further, there were some differences in how Australia responded to the societal concerns raised about potential risks of nanotechnology, given the differences in institutional, policy, and regulatory arrangements. In the context of these international nanotechnology developments, this research examines how the Australian nanotechnology sector responded to challenges posed by the potential risks of nanotechnology and presents the findings in the subsequent sections.

Risk governance framework and challenges

Studies examining potentially disruptive technologies from a risk governance perspective are growing (Read et al., 2016; van der Vegt, 2018). In this study, we apply the risk governance framework proposed by Malakar and Lacey (2020) (Fig. 1), based on the work of Renn (2008), van Asselt and Renn (2011) and Renn and Roco (2006a).

The framework has five components. Risk assessment, risk management and risk communication are the three core stages of the framework and widely accepted in traditional risk governance literature. Risk assessment includes the assessment of occupational health and safety (OHS), environmental, and social and ethical risk. Risk management includes an investment of resources, and policy and regulatory arrangements. Risk communication includes information exchanges among multiple stakeholders. Inclusion and reflection are also included in this framework as two cross-cutting elements that may occur either independently or within all three stages. These cross-cutting elements are more recent additions that seek to move beyond purely technocratic risk governance approaches (van Asselt and Renn, 2011). Inclusion emphasises involving multiple perspectives and stakeholders. Reflection is a continuous and iterative process about how decisions are made, how decisions should be made about risks, and the subsequent integration of these decisions in practice. The framework is non-linear, i.e., the components do not follow a sequential order and the two-way arrows show interconnections between the components.

The components of the framework guided our review of the international literature on nanotechnology risk governance to identify key risk-related challenges in the sector. On the basis of the review, we identified ten challenges that summarise how these risks were identified, assessed, managed, and communicated. These ten risk-related challenges from the literature are described in Table 1 and the identification of this range of widely documented challenges in nanotechnology R&D was a critical first step to identifying the type of risk governance practices employed by Australian nanotechnologists to address these challenges. This is the first time these ten challenges have been brought together to inform a risk governance assessment, and the combination of the risk governance framework and the ten challenges forms the basis of data collection and analysis in this research. While the challenges are not specific to Australia, our research focuses on how Australian nanotechnologists responded to these challenges in their practice in order to build an understanding of how risk governance to nanotechnology was operationalised in this context.

Methods

This research draws on a range of sources including literature review, semi-structured interviews with Australian nanotechnologists, and a combination of qualitative and quantitative analysis of the interview data to identify themes and generate a visualisation of interconnections between the components of the risk governance framework applied in this research. The research was undertaken as a case study, in which our focus is nanotechnology R&D in Australia, with the main objective being to identify the range of risk governance practices that have emerged and how they interact or influence one another. In this way, case study design allows us to build an understanding of these phenomena (Lapan, 2011). Case study research requires setting boundaries for the research (Stake, 1995). Hence, we set the following boundaries: Australia as the geo-political boundary; nanotechnology as the field of study; and risk governance as the conceptual approach. While this Australian case study is located within a global context, the intent is to explore the interactions, complexities, problems, or solutions that this case holds for the risk governance of disruptive technologies. In this research, we also apply a novel approach to visualising interconnections between various components of the risk governance framework.

Participant selection. Since nanotechnology R&D involves multiple disciplines and sectors, we sought to identify participants representing a range of discipline and domain areas using two methods. First, we prepared a list of potential participants from the contributors to significant national and publicly available Australian nanotechnology publications. From this list, contributors were grouped according to their expertise. From each group 2–3 participants were randomly selected and invited to participate in the study via email and telephone. Second, snowball sampling was also used to identify additional participants and ensure independent and diverse views were represented (Marshall and Rossman, 2011). A total of 28 participants were interviewed for this research. They represented broad experience across nanoelectronics, nanotoxicology, nanoethics and political philosophy, nanometrology, physics, legal and regulatory aspects, and environmental chemistry.

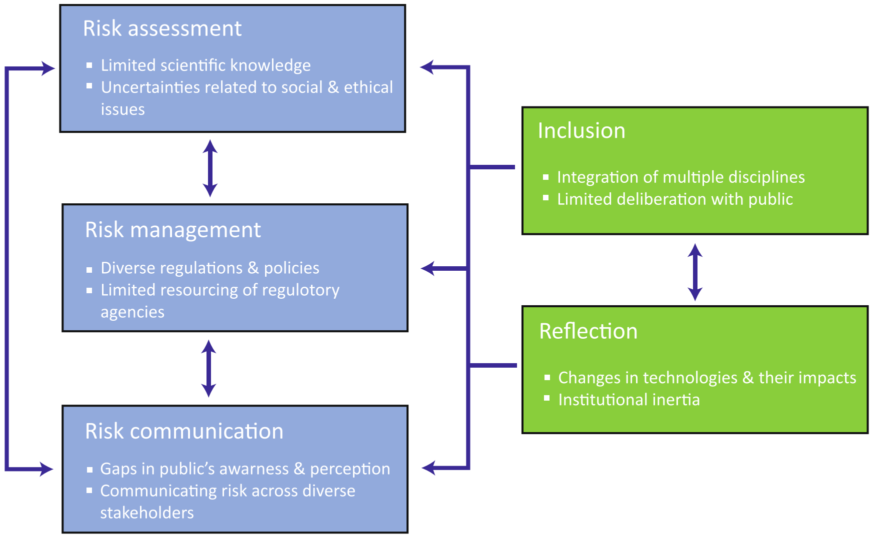

Fig. 1 Risk governance framework (reproduced from Malakar and Lacey (2020)).

Of the 28 participants, 9 were female and 19 were male with the majority from universities (13) and publicly funded research agencies (13), and single participants from industry (1) and a regulatory body (1). A primary criterion for participant selection was five or more years of experience in the Australian nanotechnology sector. The experience of participants ranged from five to more than 15 years experience in the sector (5 years = 1 participant, 6–10 years = 3 participants, 11–15 years = 9 participants, >15 years = 15 participants).

Data collection. A qualitative approach of enquiry was employed using semi-structured interviews for data collection (Minichiello et al., 2008). An interview protocol was developed and covered a range of topics including participants' experience in nanotechnology R&D, their perception of risks and benefits of the sector, risk assessment processes used in their field/domain, approaches to communicating risk, developments in regulations and policies, and other changes they had witnessed over time. All interviews were conducted via telephone, audio recorded with permission, and transcribed for analysis. On average, the interviews were 45 min in duration.

Data analysis and visualisation of results. All transcripts were cleaned and formatted for use in R software (R Core Team, 2018). Excerpts from the transcripts were manually coded using the R package for Qualitative Data Analysis (RQDA) (Huang, 2018). In the initial coding, risk governance practices were identified from passages in the transcripts. To ensure a systematic approach, a coding frame consisting of ten code categories reflecting the ten identified risk-related challenges was developed. The use of a coding frame is common in qualitative analysis and serves as an analytical instrument to classify and synthesise data (O'Connor and Joffe, 2020). It also allows unique responses to be transformed into quantitative metrics, which later allowed us to visualise the results.

To ensure reliability, each transcript was coded three separate times, resulting in a total of 571 codes, 22 risk governance practices and ten intended outcomes. After each round of coding, the codes and passages from the transcripts were independently analysed by a co-researcher. If there was disagreement, a further round of coding was undertaken. Agreement was reached after the third round of coding. After the final round of coding, internal consistency of intercoder reliability was calculated (Miles and Huberman, 1994) and found to be 87%, which is in the acceptable range of 85–90% (Castleberry and Nolen, 2018). From this initial analysis, a total of 22 risk governance practices were identified. Similar risk governance practices were then regrouped to identify the ten intended outcomes arising from the ten identified risk-related challenges.

Because the qualitative analysis was undertaken in R, we then undertook a descriptive analysis of the risk governance practices using the *tidyverse* package (Wickham, 2017). This allowed us to identify and record the frequency of topics raised in the transcripts and prepare the data for visualisation. The method of counting frequencies in qualitative data is useful if the aim of the research is not to generate new theory but rather to generate new insights into the phenomena of interest (Hannah and Lautsch, 2010). It is also useful for understanding patterns in the data and mapping those insights (Sandelowski, 2001). In this research, the frequency of responses allowed us to visualise the prominence of certain risk governance practices, and to understand the interconnectedness between the components of the risk governance framework. To ensure our analysis is reproducible and transparent, the coding is made available in an open-source platform.

For visualisation of the results of the analysis, we employed packages suitable for categorical data (i.e., data divided into categories based on qualitative characteristics). The *tidyverse* and *ggalluvial* packages (Brunson, 2020) were used to produce Fig. 2, which illustrates how each risk governance component is comprised of the identified risk-related challenges, the practices and responses employed in the sector, and how these responses advance intended outcomes in the sector. The visualisation in Fig. 2 also highlights which components of the risk governance framework were identified more frequently by participants and the relative prominence of each challenge, responses and intended outcomes as identified in the data. The *gridExtra* package (Auguie, 2017) was used to group all the five risk governance components in Fig. 2.

Finally, to produce Fig. 3, we used the *circlize* package (Gu et al., 2014) to apply a relatively new visualisation technique, appropriate for representing complex information. While circular visualisations of data are more frequently applied to large quantitative data sets (Okamura, 2019), the use of R software in this research allows for data analysis and visualisation to be generated seamlessly. In this visualisation, the interconnections between various risk governance practices are identified. The interconnections were

Table 1 Identifying ten risk-related challenges for nanotechnology R&D.

Components of risk governance framework	Risk-related challenges
A. Risk assessment—assessing occupational health & safety (OHS), environmental, social & ethical risks.	**A1. Limited scientific knowledge** In the early stages of nanotechnology R&D, limited scientific knowledge posed a challenge to developing robust risk assessments, largely because the science was still being developed (IRGC, 2006). Some challenges related to determining the potential effects of nanotechnology on human health and the environment (Renn and Roco, 2006a) and little was known about the environmental accumulation of nanoparticles (Maynard, 2006). **A2. Uncertainties related to social and ethical risks** Although policy documents and research studies acknowledged the importance of assessing social and ethical risks, doing so was challenging because it was uncertain how nanotechnology would evolve and what societal implications would ensue (Allhoff and Lin, 2008; Read et al., 2016). This uncertainty affected how such risks were considered, if at all.
B. Risk management—refers to policy & regulatory arrangements to make informed decisions.	**B1. Diverse regulatory and policy arrangements** No specific regulation was available to address nanotechnology (Ludlow, 2008; Miller and Wickson, 2015). It was also not clear how specific regulation would be applied to safeguard potential risks of nanotechnology. Initially, nanotechnology was regulated via various regulatory bodies, and coordinating a response through diverse regulatory and policy arrangements was challenging (Bowman and Fitzharris, 2007; Bowman and Hodge, 2006a). **B2. Limited resourcing of government agencies** Lack of resourcing for risk-related nanotechnology R&D, including limited funding and human resources (Renn and Roco, 2006a). Adequate resourcing is essential for improving knowledge capabilities, appropriate training and regulatory practices (development, reform and compliance) (Duncan, 2011). Challenges also arose in prioritising across multiple key areas (e.g. risks to human health were noted as taking precedence over risks to environment in some cases) (Maynard, 2006).
C. Risk communication— exchanging information, experience, knowledge, & perspectives among stakeholders.	**C1. Gaps in public awareness** As a new technology, nanotechnology raised concerns for NGOs and the public globally. Studies were conducted to understand public awareness of nanotechnology (Satterfield et al., 2009; Scheufele et al., 2009). Communicating the risks of complex technology to non-specialists was also challenging (Pidgeon and Rogers-Hayden, 2007; Scheufele et al., 2009; Siegrist and Keller, 2011). **C2. Communicating risk across diverse stakeholders** Nanotechnology involves a wide range of stakeholders, e.g. researchers, NGOs, public, industries, and media. It was challenging to communicate risks across diverse stakeholders because of their divergent interests and perspectives (Pidgeon and Rogers-Hayden, 2007; Read et al., 2016). This gave rise to extensive scholarship on risk communication, with particular focus on the importance of multi-stakeholder deliberation (Jones et al., 2014; Krabbenborg, 2012).
D. Inclusion—involving stakeholders from various sectors and disciplines.	**D1. Integration of multiple disciplines** Nanotechnology R&D and risk governance requires input of multiple disciplines (Renn and Roco, 2006a). Ensuring multidisciplinary inputs was challenging due to differences in scope, underpinning concepts, and methodologies (Renn and Roco, 2006a; Russell, 2013). However, doing so was critical to address not only technical risks but also social and ethical risks (Fisher, 2005). **D2. Limited deliberation with public** In the early stages of nanotechnology R&D, communicating risks and benefits with the public was largely a one-way supply of information from scientists and/or policymakers (Keller, 2006). Establishing two-way and on-going dialogue throughout the innovation process was identified as a challenge by scientists and policymakers (Kahan, 2009; Macnaghten and Chilvers, 2012) but increasing examples of public engagement have been documented in the literature (e.g. the NNI's efforts, Alexander et al. (2006).
E. Reflection— demonstrating a practice of reflexivity.	**E1. Evolution of technologies and their impacts** Governing risks of nanotechnology requires constant review of risk framing and risk decisions. The ability to reflect on changes was identified as challenging because nanotechnology applications were constantly evolving (Renn and Roco, 2006b). With no review mechanisms in place, it was challenging to address new risks and understand the public's acceptance of nanotechnology (Jones et al., 2014). **E2. Institutional inertia** The nanotechnology R&D sector was undergoing constant evolution and development of science, which required ex ante methods to help anticipate and plan for potential consequences (Porcari et al., 2019). This created a need to move beyond simple cause-and-effect approaches to more proactive and iterative forms of adaptive management. It was observed this could be challenging in the face of institutional resistance to change (Renn and Roco, 2006b).

identified from the transcripts where participants described how practices contributed to one or more of the ten intended outcomes for the sector. That is, if two or more risk governance practices were coded from the same excerpts of a transcript, a relationship was identified. For example, if a participant described how engaging with the public also enabled the development of risk policies, a connection was made between public engagement and policy development. Additionally, we ran a frequency analysis to generate how many times an intended outcome was related to other intended outcomes. Finally, we aligned the ten intended outcomes with the five components of the risk governance framework.

Identifying nanotechnology risk governance practices

The interviews identified a range of professional practices that had been adopted or implemented in response to the ten identified challenges. Thematic analysis of these practices was then undertaken and generated 22 risk governance practices aligned with ten intended outcomes (Fig. 2).

In this research, risk governance practices represent the professional practices, as described in the interviews, that were adopted or implemented to address the ten identified risk-related challenges. These risk governance practices were thematically grouped to generate the ten intended outcomes they were contributing to. Simply put, to address the ten identified challenges, 22 risk governance practices were adopted and implemented to advance the nanotechnology sector towards ten intended outcomes. We summarise the key findings about risk governance practices against each component of the risk governance framework below.

Risk assessment practices. In response to the two identified risk assessment challenges of limited scientific knowledge and social and ethical uncertainties associated with nanotechnology R&D, the two intended outcomes of *increased scientific knowledge* and *social and ethical integration* were identified from the interviews. These intended outcomes were generated by grouping similar meaning risk assessment practices corresponding to the challenges. Participants reported three risk governance practices to increase scientific knowledge (130 times) and two risk governance practices to improve social and ethical integration (35 times) (Fig. 2a). One participant who managed nanotechnology projects in a publicly funded research agency highlighted that "*in the last 15 years, I have seen extensive work done in the fields of toxicology, ecotoxicology…we have very much narrowed down the questions or the areas of concern around risk to a very small family of nanoparticles. And our modelling skills have advanced. So, we are better at predicting where potential risk may lie*" [I 12]. Although early nanotechnology risk research globally did not always prioritise the examination of environmental risks (Maynard, 2006) (e.g. in the United States, the National Nanotechnology Initiative invested just 0.5% of its total funding in examining the environmental implications of nanotechnology from 2000 to 2004 (Dunphy Guzmán et al. 2006), participants provided examples of environmental risk research in Australia, such as soil and water contamination of nanoparticles. In this research, participants also frequently coupled human health and environmental risks when describing their risk assessment processes, indicating these areas were seen as interrelated. Referring to the sunscreen concerns, one nano physicist said, "*…in the areas where I was working, we would look at the risks from a health and safety and environmental risk [perspective]…*" [I 5].

Practices to integrate consideration of social and ethical risks were less frequently reported than those related to increasing scientific knowledge, yet the results demonstrate an awareness of both the physical and less tangible aspects of risk governance. Proponents of risk governance argue that risk assessment must consider physical risks along with social and ethical risks, in which both objective and subjective evaluations are critical (Renn, 2008). Participants reported practices to minimise both types of risk in their work. For example, they carried out quantitative studies to assess the likelihood of risk to human health and the environment, which increased scientific knowledge in the field. In addressing social and ethical risk assessment, participants spoke of being involved in organised public engagements designed to identify broad social and ethical concerns. Engaging with stakeholders, including the public, to anticipate social and ethical implications of nanotechnology was adopted around the world. For example, the Dutch government facilitated a social dialogue about nanotechnology involving a wide variety of stakeholders (CieMDN, 2011). Similarly, the NNI organised a workshop to enable public participation in assessing social implication of nanotechnology (Alexander et al. 2006). In Australia, addressing concerns related to the use of nanoparticles in sunscreens was identified as a core social responsibility of scientists, as one semiconductor scientist explained, "*we got involved in a range of studies under the preventative health category, as a response to the [sunscreen] question posed by the public… We were looking at… what are the mechanisms by which these [sunscreens] can cause damage [to human health]. It was a social licence to operate*" [I 2].

Risk management practices. To address the two risk management challenges of diverse regulations and policies and limited resourcing of government agencies, participants reported undertaking risk governance practices to advance the two intended outcomes of *robust regulations and policies* (49 times) and *increased government funding of nanotechnology risk research* (49 times) (Fig. 2b). Effective risk governance requires appropriate regulations and policies supported by adequate resourcing (Renn and Roco, 2006b). This can be achieved by developing or updating regulations and policies to address potential risks so that sufficient safeguards are in place (Bowman and Hodge, 2006a). For example, the European Union (EU) and the NNI have policies in place to fund projects to assess and manage both physical and social risks (Duncan, 2011). In this study, participants identified working collaboratively with regulators and policymakers to provide scientific information to underpin or strengthen relevant regulations and policies. To inform government policy makers, one participant, working in nanotechnology policy, described that they looked "*at the readiness of different regulatory frameworks to manage nanotechnology…in relation to areas that nanotechnology was having an effect on*" [I 23].

A lack of specific nanotechnology regulation was identified as a challenge in the literature and governments around the world undertook initiatives to examine and revisit whether their existing regulations sufficiently addressed the potential risks of nanotechnology, e.g. the European Commission specifically examined the regulatory aspects of nanomaterials (European Commission, 2008). In Australia, a similar study was conducted by Ludlow et al. (2007), which identified that existing regulatory frameworks were well suited to regulating nanotechnology for the next decade. In a similar vein, participants indicated that the regulations of the time had helped them develop new nanotechnology-related risk policies and provide support to stakeholders, including the public and industry. In relation to developing new risk policies, one physics researcher, described that "*they [legislators] put up a new legislation how to deal with particles smaller than 100 nanometres in order to ensure that the people who are working [with nanoparticles] have appropriate protection*" [I 16]. In this research, evidence-based science was

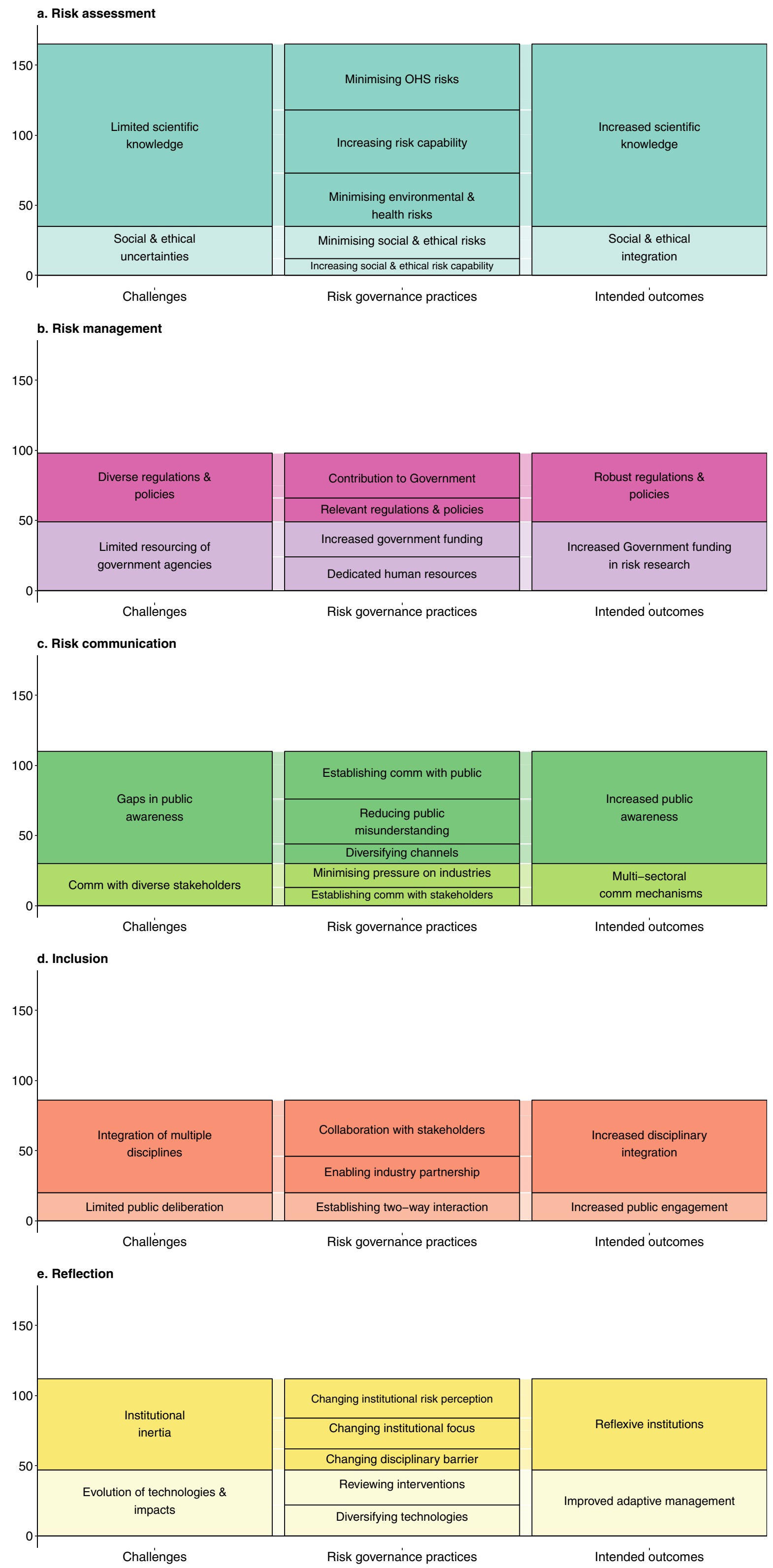

Fig. 2 Risk governance challenges, practices and intended outcomes. Note: There are five panels (from 2a to 2e) in the figure corresponding to the five risk governance components. The size of each risk governance practices box represents the total count/frequency, indicating the relative prominence of these practices being identified in the data. The challenges, risk governance practices, intended outcomes, and their frequencies are supplied in Supplementary Note 1, Supplementary Tables 1–5.

reported to be critical to those interactions between scientists, policy, industry (Kah et al., 2018; Obermeister, 2020) and the public, demonstrating the multi-stakeholder nature of risk governance.

Risk communication practices. In addressing the two risk communication challenges of gaps in public awareness and communicating with diverse stakeholders, participants described risk governance practices targeting the two intended outcomes of *increased public awareness* (80 times) and *multi-sectoral communication mechanisms* (30 times) (Fig. 2c). *"The awareness now is much broader in the community"* [I 15], stated one scientist working on nanostructured films, to describe how their work contributed to increased public awareness. The need to communicate the potential risks and benefits to non-experts through two-way public discourses is extensively discussed in the international literature (Bostrom and Löfstedt, 2010). In this research, participants largely described the role of risk communication as being to raise awareness or educate the public about new applications of nanotechnology. However, it was also evident that some efforts were made to establish two-way communication with the public and other stakeholders about the potential risks of nanotechnology. In relation to the sunscreen debate, one academic reported that "*there were a lot of [public] concerns [about nanoparticles in sunscreens], and by being open-minded and interacting with the community…[we] were able to really address the community's concerns, and the community is not worried anymore*" [I 28]. Dialogues of this nature tended to occur during public meetings and face-to-face consultations and open forums, which took place around 2007–08 in Australia at the height of the debates about nanoparticles in sunscreens.

Communicating scientific findings to a lay audience is key to managing expectations and concerns; it requires a mutual-learning approach, in which both experts and non-experts can provide input (Cormick, 2012; Dudo et al., 2014; Garard et al., 2018). Studies suggest undertaking various measures to communicate the potential risk to the public, including but not limited to labelling of nanotechnology in consumer products (Siegrist and Keller, 2011). In Australia, there is no mandatory labelling of nanotechnology, and there was no unequivocal agreement among research participants whether it should be practised as a means to communicate risk. Participants, however, identified several communications channels and mechanisms, such as audio-visual presentations and the media. Describing the multiple ways they communicated with stakeholders, one scientist, working in environmental chemistry, described, *"we used to get a lot of media enquiries, where we were doing either radio or TV interviews. The community, a lot of times, would even just come directly to [our organisation], asking for information*" [I 11]. Although risk communication can be challenging due to the diverse worldviews of multiple stakeholders (Renn, 2008), the risk communication practices described in this research suggest such processes can be facilitated through increased public awareness and stakeholder engagement.

Inclusion practices. To address the two inclusion challenges of integrating multiple disciplines and limited public deliberation, participants described risk governance practices contributing to the two intended outcomes of *increased disciplinary integration* (66 times) and *increased public engagement* (20 times) (Fig. 2d). Increased disciplinary integration was advanced by practices such as studying the potential risks of nanotechnology across domains such as human health, the environment, and social sciences in the R&D of nanotechnology. An expert in carbon nanotubes emphasised that they "*were working with the social scientists in the nanotechnology office of the Department of Industry*" [I 3]. Another participant, working in the university sector, described that their project had people from various disciplines and explained, "*I primarily worked in the physical sciences with chemists, physicists, mathematicians, [and] engineers*" [I 22]. Participants identified working across different sectors as key to generating broader perspectives and new knowledge. The integration of multiple disciplines in nanotechnology R&D was discussed extensively in the literature. For example, following the introduction of the nanotechnology Act of the United States, 'socio-technical integration' has been identified as an important approach to enable technical experts to take social implications into considerations (Fisher, 2019). There were global calls to adopt multi-disciplinary approach in nanotechnology (Rodríguez et al., 2013), and the Australian R&D sector benefited from those initiatives.

While inclusion is a key principle of risk governance that enables collective learning, it is not always simple to operationalise in practice, especially where risks are uncertain and ambiguous (Irwin, 2014; van Asselt and Renn, 2011). To operationalise inclusion in nanotechnology R&D, formal approaches such as upstream engagement (Krabbenborg and Mulder, 2015; Pidgeon and Rogers-Hayden, 2007) and midstream modulation (Fisher et al., 2006) were put forward in Europe and the United States. The former underlines the engagement of the public from the early stages of innovation, whereas the latter highlights more reflexive processes to include voices of a wide range of stakeholders to address and adopt necessary changes based on evolving circumstances. In Australia, the efforts to include public were less formalised in methodological terms however were closer to a reflexive midstream intervention than an upstream engagement. Given the concerns around nanotechnology in sunscreens in Australia (Faunce, 2010), public dialogues were organised to provide the public with access to experts to answer their questions and respond to their concerns. Participants also highlighted their engagement with industry stakeholders, and one nanotoxicology scientist stated that "*we did collaborate with industry… that was collaborating with an independent Australian sunscreen company*" [I 9] to manufacture new sunscreens. Another nanotoxicology academic highlighted the benefits of engaging with public as follows, "*I think that is an important part of co-creation because you bring that aspect to the public's viewpoint too. Otherwise, they [would] think everything was done behind closed doors*" [I 25].

Reflection practices. In response to the two reflection challenges of institutional inertia and evolution of technologies and their impacts, participants described risk governance practices aimed at advancing the two intended outcomes of *reflexive institutions* (65 times) and *improved adaptive management* (47 times) (Fig. 2e). The purpose of reflection in risk governance allows stakeholders to review their fundamental assumptions for innovation and revise where appropriate (van Asselt and Renn, 2011). At the institutional level, reflexivity can be useful for examining commitments and being aware of underlying limitations (Stilgoe et al. 2013). Additionally, it helps to critically assess the direction of R&D in the midstream of innovation, so that necessary changes can be adapted and adopted based on the evolving circumstances (Fisher et al., 2006) and is also integral to the theoretical dimensions of responsible innovation (Owen et al., 2013). In relation to reflexivity, participants explained their institutions had made a series of shifts, which had been reflected in changes in organisational risk perception and new approaches to designing projects (i.e. interdisciplinary, cross-sectoral). In providing an example of a change in their organisation's risk tolerance, one material scientist explained, "*the actual work [around carbon nanotubes] wound up before we had something we could get out into the world and be useful, and, I guess, the uncertainty around the safety of the material was part of the decision process. We could keep investing and we may solve the problems and get a good material…what if it turns out to be a dud material anyway*?" [I 10]. In this case, the potential negative health impacts outweighed the benefits of continuing the research.

Reflection enables systemic changes that could be critical to mainstream risk governance principles into responsible innovation (Stilgoe et al., 2013). Earlier studies proposed various measures to embed reflexivity into innovation, such as the constructive technology assessment, which identifies institutional realisation and change of directions as examples of reflexivity (Rip and Robinson, 2013). Similarly, participants, in this study, described their institutions making changes and becoming more sensitive to a broader range of risks, and even ceasing work on some applications, such as carbon nanotubes due to their potential safety issues to scientists. This provides evidence of revising risk decisions based on the information generated through new research and risk assessment. One environmental scientist who had worked with carbon nanotubes expressed their own questioning of previously accepted research approaches, "*the question was, is an artificial or a manufactured nanomaterial different from a natural one? That was the question we were trying to answer. Do we need to actually come up with a different way of assessing their risk*?" [I 11]

In summary, a range of risk governance practices was identified addressing the ten challenges, which in turn contributed to advancing ten intended outcomes in the sector. These intended outcomes were also shown to be interrelated and interconnected. Multiple stakeholders were involved in the risk governance of nanotechnology R&D in Australia, including scientists, policymakers, public, industry, and media; their roles variously intersecting and contributing to the progress and development of the sector. In the next section, we demonstrate how this risk governance approach was operationalised in the Australian nanotechnology R&D sector and visualise the interactions between the practices undertaken by various stakeholders to achieve progress toward the intended outcomes.

Australian nanotechnology risk governance approach

This section presents a quantitative visualisation of the risk governance approach that has been operationalised in the Australian nanotechnology R&D sector. Importantly, we demonstrate the interconnections between (a) the risk governance practices undertaken to progress towards the ten intended outcomes, and (b) the five components of the risk governance framework. Figure 3 visualises these interconnections, which is a key contribution of this research.

Figure 3 illustrates the non-linear nature of risk governance of nanotechnology R&D in Australia. The circular shape of the figure allows the multiple interconnections between the risk governance practices to be established and shown holistically. This provides a way of visualising complex interconnections and highlighting that risk governance processes occur simultaneously and non-sequentially. The chords in the inner circle show the interconnections identified between the ten intended outcomes. The size of the chords depicts the frequency of the connections, that is, the wider the chords, the higher the number of times participants identified connections between these intended outcomes. The interconnections between these outcomes also demonstrate how risk governance practices are linked to each other.

The results of this study identified that the risk management component of the framework has the most connections with the other components (68), followed by risk assessment (43), inclusion (44), risk communication (39), and reflection (39). The frequencies of the interconnections between risk governance components are provided in Supplementary Table 6. This means participants discussed the connections between the risk management practices and the other practices with the highest frequency. In developing regulatory safeguards to manage potential risks associated with nanotechnology, Bowman and Hodge (2006a) argue for governments to be proactive in engaging with stakeholders. While providing an example of the government's proactive engagement with multiple stakeholders in assessing the potential risk of nanotechnology, one scientist who had worked in carbon nanotubes highlighted, "*…together with [deidentified] from the National Measurement Institute, I coordinated Australia's involvement in that programme [international project on nano safety] … It involved the Therapeutic Goods Administration, the food regulator, the chemical regulator, the environmental people et cetera*" [I 3]. This quote highlights interconnections between risk management, risk assessment, and inclusion. Such interconnections were not only limited to risk management, and all risk governance components were found to be interrelated, highlighting the nature of risk governance of nanotechnology in Australia.

Given that inclusion and reflection are newer additions to traditional risk governance approaches (van Asselt and Renn, 2011), we note that both cross-cutting elements were evident in the range of practices and clearly visible in Fig. 3. As with the more traditional stages of risk governance, inclusion and reflection were also found to be interconnected with the other components of the framework. Although there are challenges in the integration of social sciences, biophysical sciences, and non-academic stakeholders (Morris et al., 2011), participants described the importance of having a multi-stakeholder engagement in increasing public awareness, contributing to policy development, and assessing risks of nanotechnology. To increase knowledge among various sectors, one academic, working in the regulatory aspects of nanotechnology, stated, "*We actually had concurrent discussions on the [nanotechnology] science … And by that, I mean within government, within regulatory bodies, within the private sector, within the academic community*" [I 24]. Another participant, a nanotechnology policy expert, described these discussions on risk assessment as beneficial because "*…the public was increasingly informed and active in the dialogue around emerging technologies in a way that was not possible before [in the R&D of new technologies]*" [I 23].

Similarly, participants highlighted that undertaking iterative reviews and discourses about risk decisions contributed to and benefited from activities occurring within the other components of the framework. For example, a nanotechnology outreach professional explained that they ran a project to study whether sufficient regulations and legislations safeguards were in place around the R&D of nanotechnology, particularly in relation to its potential risks. While linking risk communication and reflection, the participant stated, "*[We] were trying to get ahead of public concern by being open and trying to [anticipate] what people might think…and also [we were] being a little more cautious around the adoption of the new technology*" [I 20]. The operationalisation of inclusion and reflection demonstrates a shift beyond purely technocratic approaches to risk, and this case study describes how this has happened in the Australian context.

At the intended outcome level, the outcome of increased scientific knowledge associated with risk assessment was found to have the second-most connections with other outcomes, whereas the social and ethical integration outcome was found to have the

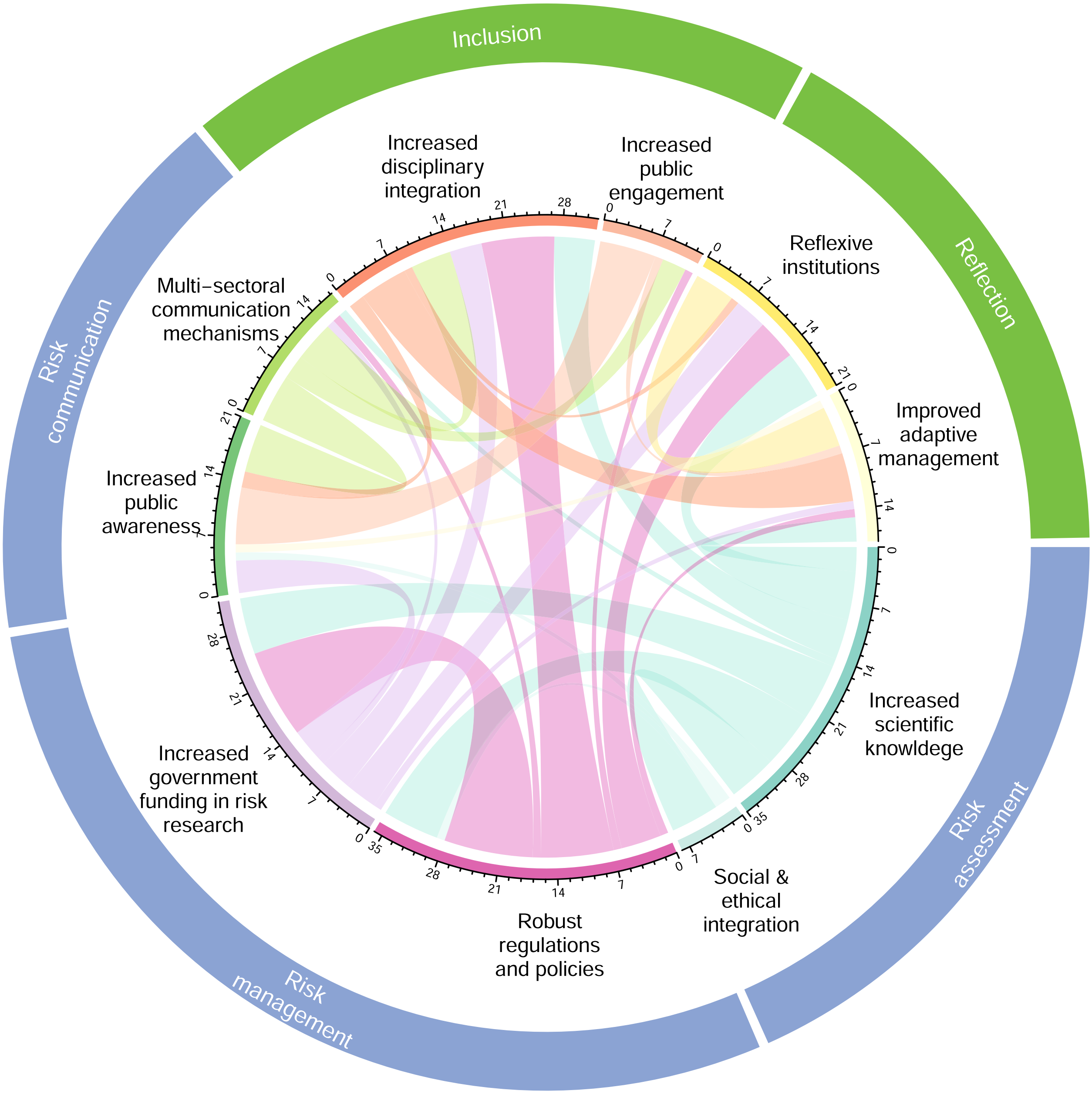

Fig. 3 Nanotechnology risk governance model. There are ten segments on the inner circle corresponding to the ten intended outcomes, represented by different colours, and five segments on the outer circle, corresponding to the five risk governance components. The segments vary by their sizes. The sizes of the intended outcomes represent the total number of connections each outcome has made with other outcomes, i.e., the more the connections, the wider the section. The chords show the connections between the outcomes. The width of the chords shows the frequency of the connections, i.e., the more the connections between the outcomes, the wider is the chord.

lowest number of connections. This indicates that practices identified as contributing to increasing scientific knowledge about the potential risks of nanotechnology both benefited from and contributed to the other outcomes. The practices identified by participants were mostly linked to intended outcomes associated with risk management, along with reflexive institutions (reflection) and increased disciplinary integration (inclusion). In emerging fields, anticipating broader societal impact is critical (Fisher and Maricle, 2015; Kato-Nitta et al., 2019). In this study, participants provided examples of technical experts working across domains such as public health, environment, and society, and across sectors of science, industry, government, NGOs/CSOs and media. Socio-technical integration scholars argue that disciplinary collaboration is needed to address societal needs and aspirations through innovation (Fisher, 2019; Rodríguez et al., 2013) and a critical building block for risk governance (Renn, 2008). However, this study also points to the limited nature of recognising social and ethical risks in a broader range of the intended outcomes. That is, fewer connections emerged between social and ethical integration and other intended outcomes reflecting that while there was some engagement with the social sciences, it has been a lesser focus in the Australian nanotechnology R&D sector. The existence of these interconnections shows how continual and multi-layered interventions are required to address risk-related challenges associated with emerging technologies.

In a risk governance approach, risk decisions are the results of multi-actor processes (Renn, 2008). In Fig. 3, we see various practices and outcomes relating to a range of stakeholders. The connections between the risk governance practices demonstrate the connections between the roles these stakeholders have played in the risk governance of nanotechnology. For example, the connections between risk assessment and risk management highlight scientists, who assess the potential risks of nanotechnology, also using their expertise to assist policymakers. Similarly, evidence of connections between inclusion and risk management infers the role of the public influencing policy development. In the interviews, participants emphasised the importance of scientists being involved in public events with government representatives. The role of the media in risk communication was found to be connected to increasing public engagement, assessing various risks, and supporting government research. The ability to quantitatively visualise the empirical insights in this case study reveals a greater level of complexity and nuance to the risk governance modalities employed by multiple stakeholders across the Australian nanotechnology R&D sector. This risk governance approach also highlights the mutually reinforcing effect of the engagement of multiple stakeholders in the overall risk governance of nanotechnology R&D.

Discussion and conclusion

To summarise, we conducted a retrospective study to explore how nanotechnology R&D is shaping risk governance practices in Australia. We identified ten nanotechnology risk-related challenges from the international literature and documented 22 risk governance practices used by Australian nanotechnologists in response to those challenges, based on interviews. These practices were aligned with progressing ten intended outcomes for the sector. We then used data counts to visualise the complex interconnectedness of the various components of a robust risk governance approach. The visualisation of the data also demonstrated the multi-stakeholder participation implicit in the effective risk governance of nanotechnology R&D.

The ten risk-related challenges were globally relevant to nanotechnology R&D. However, this is the first time these challenges have been synthesised and used to frame a risk governance assessment for a particular country context. For this reason, we believe this Australian case study may provide lessons that can be replicated not only for other country contexts but also for other technologies. The findings of this research indicate that nanotechnology R&D in Australia contributes to risk governance scholarship and practice in several ways.

First, unlike traditional risk assessment approaches that are solely based on a single discipline and use the probabilistic estimation of physical risks, Australian nanotechnology risk governance demonstrates interdisciplinary risk research that recognised the importance of assessing not only public health but also environmental and, albeit to a lesser extent, social and ethical risks. The organisation of public consultation to explore social and ethical implications of nanotechnology demonstrates a concern to broaden technical risk assessments. This was undertaken, we argue, because the proponents of nanotechnology recognised their own roles in minimising potential risks of the technology. This was also influenced by experiences of the rejection of other technologies such as genetically modified organisms where the value of assessing social and ethical risks had not been sufficiently considered prior to their market introduction (Krabbenborg and Mulder, 2015).

Second, although no regulation specific to nanotechnology was developed in Australia, the findings demonstrate that government stakeholders played a proactive role in engaging various stakeholders in relation to safeguarding human health, the environment, and society from potential and perceived nanotechnology risks through the development of appropriate regulatory arrangements.

Third, the importance of integrating reflexivity and inclusion into the process of innovation has received extensive attention in the science, society and technology scholarship (Fisher et al., 2006; Rip and Robinson, 2013) but the operationalisation remains challenging. Although approaches to operationalising inclusion and reflexivity were methodologically less formalised in Australia, we found evidence of inclusion and reflection practices in the Australian nanotechnology R&D, demonstrated by examples of participatory processes and a commitment to openness and transparency (van Asselt and Renn, 2011).

This case study generates two important implications for the risk governance of future and emerging technologies globally. First, scholars, such as Renn and Schweizer (2009), Boholm et al. (2012), and Scheer (2013), emphasise the non-linear nature of risk governance and that it is fraught with multiple iterative processes that are interconnected. The findings suggest that nanotechnology risk governance is a non-linear process, that risk governance practices employed by Australian nanotechnologists are not only interconnected but can be visualised and understood as we have demonstrated in this study. For example, the results show that these practices did not occur in isolation but concurrent with and contribute to each other. That is, practices employed to address one challenge have effects on addressing other challenges, thereby strengthening risk governance. For example, scientific studies to assess the potential risk of nanotechnology have made contributions to inform policies. Additionally, the potential disconnects between the work of scientists, policymakers and the public has been highlighted as a persistent challenge in science and society scholarship (Dietram et al., 2007; Farley-Ripple et al., 2020; Nordmann and Rip, 2009; Satterfield et al., 2009). This study demonstrates applying a risk governance approach enables greater intersection and collaboration among those roles. Importantly, these interconnections between the risk governance practices and the iterative nature of these practices inform how and why multitudes of practices are important for the risk governance of emerging technologies.

Second, governing potential risks and benefits of disruptive technologies is a non-hierarchical multi-actor process, where all stakeholders play their part (van Asselt and Renn, 2011). This study exemplifies that underpinning the risk governance of nanotechnology R&D in Australia was the contribution of a wide range of stakeholders, including scientists, public, policymakers, media, and industry. For example, the role of science was to produce evidence by conducting scientific studies, such as assessing the potential risks on human health and the environment. The findings of these studies were communicated with policymakers, the public and industry through various forums. The roles of government and policy were to create an enabling environment for science, develop regulatory frameworks to minimise the potential risks of nanotechnology, and communicate with the public together with the scientific community. The role of the public was to engage with science and policy communities and exchange knowledge, concerns, and experiences. Although all actors have a crucial role to play in risk governance, not all take the lead on all practices. For example, the public can inform science and policy about their needs and concerns and help science to co-design scientific undertakings (Bendixen, 2020; Matta, 2020). This also highlights that risk governance is not purely a process to be applied ‘downstream’ of technology development. Rather it begins at the earliest stages as basic research is undertaken and potential applications are being explored so that informed decisions can be made throughout the R&D of emerging technology.

This case study also identifies areas for improvement in the risk governance of future technologies. It was evident in the findings that Australian nanotechnology R&D has focused on increasing public awareness through science, which exemplifies a science-centric approach to risk communication. Although we documented the implementation of two-way exchanges between scientists and the public, a mutual-learning approach delivers benefits beyond approaches that favour science alone (Cacciatore, 2014; Toumey, 2011). Further, the interactions between the integration of social and ethical risks and the other intended outcomes were found to be the lowest in this study, which reflects that while the formal methodologies and approaches for this type of risk assessment have been lacking, as argued by Brom (2019), the issues were acknowledged nonetheless. Socio-technical integration scholars highlight that embedding social and ethical aspects in R&D processes is vital to address societal expectations and aspirations in innovation (Fisher, 2019). We emphasise the use of data analysis and visualisation techniques to identify interconnections between risk governance practices as providing a novel opportunity for developing systematic methodologies and measures to better enable this integration in the risk governance of emerging technologies.

To conclude, technologies are emerging at an increasing pace and decision-makers are grappling with ways to deliver responsible science and technology by assessing the balance between the potential risks and benefits of these technologies. This study has shown that the risk governance of emerging and potentially disruptive technologies can never be a single assessment (Macnaghten and Chilvers, 2012), but rather a continuous and iterative process involving multiple stakeholders and actors interacting to achieve a broad range of intended outcomes. Risk governance enables a platform for a wide range of stakeholders to work together in this way and the framework used in the study is highly adaptable to other new and emerging technologies.

Limitations and future work. There are some limitations of the study, which require further research. Central to our study was exploring how nanotechnology challenges were addressed by Australian nanotechnologists through their own practices and responses. As we have found, a wide range of risk governance practices was carried out by diverse stakeholders. The findings reveal not only the complexity and intricacies of these responses but also the possibilities and opportunities for the risk governance of nanotechnology. Our scope was not to evaluate the effectiveness of those practices in responding to the challenges, but rather to demonstrate a risk governance approach that usefully identifies the range and breadth of these practices among multiple stakeholders and how they have shaped risk governance of nanotechnology R&D in Australia. It would be beneficial to undertake studies to find out what worked and what did not. We recommend carrying out an evaluation aligned with the risk governance components.

As our objective was to deeply engage with experts who have worked in the nanotechnology field to understand their perspectives, experiences, and practices in relation to the potential risks and benefits of the technology, we employed a qualitative data collection with a small sample size. The findings are by no means a representation of the entire nanotechnology field in Australia. Further research to test how widespread these practices continue to be or how they are evolving would be beneficial and we believe our study provides the foundation for such research.

Data availability

As required by the conditions of the human research ethics clearance for this research and as stated on participant consent forms, the raw interview transcripts are restricted. However, a set of source data to reproduce the visualisation is publicly available along with the data analysis codes at https://doi.org/10.25919/1cv0-pa77.

Code availability

For data analysis, R software is used. All the codes and source data are publicly available at https://doi.org/10.25919/1cv0-pa77.

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Competing interests
The authors declare no competing interests.

Ethical approval
This research was approved by CSIRO's Social and Interdisciplinary Science Human Research Ethics Committee in line with the guidelines specified in the (Australian) National Statement on Ethical Conduct in Human Research.

Informed consent
The authors confirm that informed consent was obtained from all participants prior to data collection.

Additional information
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