Climatic Change (2025) 178:44
https://doi.org/10.1007/s10584-024-03854-8

Navigating complex waters: Designing a process for the development of the National Climate Assessment

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Received: 21 May 2024 / Accepted: 28 December 2024 / Published online: 3 March 2025

Abstract
Scientific assessments are tools used to look across a broad body of knowledge and draw overarching conclusions about the state of the science. They allow experts to synthesize technical knowledge and develop broad understanding of observed and future trends, risks, and opportunities. The National Climate Assessment (NCA), a major climate report of the United States (U.S.) Government, is one such assessment report. The NCA was created by Congressional statute and is classified as a Highly Influential Scientific Assessment, which results in a wide range of obligations, as well as required compliance with various statutes and other federal policies and procedures. The NCA also represents a unique effort to bring together federal agencies, the scientific community, and users of climate science throughout the U.S. to empower decision-making, build consensus, and drive climate actions. Innovations in the NCA development process over multiple cycles of the report's development were implemented to meet both evolving legal requirements and user needs are described in this paper to share institutional knowledge and best practices with those assessment developers who might be navigating similarly complex constraints. This paper seeks to summarize that history and draw out some valuable lessons for future interagency assessment development teams. A discussion of critical innovations, including expansion of technical resources, knowledge bases, and communication tools, is included to inform the development process of future scientific assessments.

Keywords Climate change · Assessment · Sustained assessment · Statutes

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1 Introduction

1.1 Defining scientific assessments

Scientific assessments are expert evaluations of bodies of relevant information with the purpose of developing synthesis products that inform decisions. The pool of available knowledge that might be relevant to an assessment can be significant, including a wide variety of peer-reviewed literature across multiple disciplines, datasets and model outputs, government reports, Indigenous Knowledges, traditional and local knowledges, and other forms of technical inputs. Assessments commonly rely on the professional expertise and judgment of authors to draw conclusions, weigh uncertainty, and identify information gaps or research needs (OMB 2004; Jacobs et al. 2016; USGCRP 2022). Based on the evaluation of these wide knowledge bases, authors are often asked to make statements defining the confidence in and/or likelihood of a specific conclusion or outcome (Crimmins 2020).

Because scientific assessments synthesize information from a broad range of information sources and are designed to be used by decision-makers, they differ in format, scope, and purpose from most of the underlying sources. For example, an individual paper or literature review may include citations to dozens or even several hundred references. By comparison, an assessment may include thousands of references, with authors being responsible for the review of tens of thousands of sources of information during development. NCA5, for example, had nearly 9,000 references cited, and tens of thousands of references reviewed by author teams during development (Maycock et al. 2023). Assessments also typically have higher bars for public engagement and peer review than individual journal articles (see section below on Core Requirements of NCA). Table 1 demonstrates differences between assessments and two types of underlying information sources: literature reviews or meta-analyses and a standard peer-reviewed research article.

Assessments are a broadly used tool to support climate decision-making. The First Assessment Report of the International Panel on Climate Change (IPCC) was published in 1990, and iterative assessments since have been major driving forces for climate discussion and action worldwide (IPCC 1990). National assessments, including the United States (U.S.) National Climate Assessment (NCA) and other assessments in the United Kingdom, Canada, and other countries have increased over time (Bush and Lemmen 2019; Krishnan et al. 2020; UK 2022). Within the U.S., subnational assessments, both at the state and local level, have proliferated as science has advanced toward increasingly localized climate knowledge (California 2018; Widhalm et al. 2018; Jersey 2020, Wisconsin 2021; Wuebbles et al. 2021; Fleishman 2023; Stevens and Lamie 2024). The development process for each of these varies widely. Local needs and governance systems have huge impacts on the process of development and ultimately the final product (Weingartner et al. 2018).

1.2 Why do assessments matter?

Assessment authors weigh scientific certainty across a wide range of information sources and present consensus conclusions in a format that informs decision-making (Crimmins 2020). Because authors review thousands of information sources and the assessment development process is so robust, assessments are extremely useful tools that users could rely on when developing informed, targeted, and effective policy in many different sectors

Table 1 Comparison in purpose, scope, and other characteristics of three types of scientific writing formats: individual research papers, literature reviews, and scientific assessments. Moving from left to right, each column represents an increase in scope and complexity and build upon each prior category. The examples are generalized and designed to highlight differences in the various products; they are not meant to serve as comprehensive summaries. While a research paper is used as an example in this table, other types of sources are also critical inputs to assessments, including non-governmental reports, state or local actions, datasets and models, indigenous knowledges, etc

	Individual Paper	Literature Review	Assessments
Primary Audience	Scientists within a topically specific research space	Targeted scientific field or community	Decision-makers, often non-scientists, including government officials and the public
Contributors	One to a small group of experts	Group of topical experts	Large and varied group
Scope	Individual hypotheses	Topically focused	Broad, complex
Identifies gaps in…	Topic-relevant knowledge	Topic-relevant literature and methodologies	The scientific information needed to reduce uncertainty and inform decisions
(Un)certainty statements	Specific to individual study conditions and results	Represents variance in available studies or methods reviewed	Holistic consideration of all sources to inform risk management decisions
Expert evaluation of (un) certainty levels	Focused on data interpretation (e.g., confidence intervals, caveats to the study)	Based on data interpretation of metanalysis and state of the field or practice	Well defined criteria, often use of standard calibrated confidence and likelihood language
Coverage of topics & sources	Often focused to the conditions of the study	Often summarizing, can be exhaustive, historical	Targeted, user-driven to inform decisions
Synthesis	Not applicable	Often but not required	Essential, required

(Maycock et al. 2023; Crimmins et al. In preparation). For example, assessed scientific information can help federal employees design better grant programs, state officials better future-proof infrastructure, and individuals make better economic decisions.

Assessments also function as tools to overcome a critical but difficult connection between research and action. The rate at which climate data and information is now being generated has greatly increased over the past few decades. This expanding resource pool has historically been inaccessible to most people outside the scientific community. Even as our understanding of climate changes and impacts continues to improve, and as climate data becomes more available and accessible, many government officials, resources managers, private companies, or individuals may lack the time, resources, or interest in developing their own climate assessments. Many decision-makers, especially policymakers, need to be able to quickly reference, understand, and employ the most up-to-date information to manage present-day risks associated with climate change, let alone to plan for potential

future impacts (NSTC 2023; NASEM 2024). Assessments serve a critical role in presenting current, clear, and trustworthy scientific information in a digestible and accessible way to decisionmakers, who can then use that knowledge for their own unique situations to take more informed actions. The emergence of climate services and responsive technology as a focus of both the public and private sectors is another positive step in this direction.

Climate services are "scientifically based, usable information, products, and activities that enhance knowledge and understanding about the impacts of climate change on potential decisions and actions" (USGCRP 2024a). Climate services can provide the hyper-local, issue-specific, and sometimes real-time data needed to solve individual problems or questions while climate assessments provide the needed context, interpretation, and translation of said data, including evaluation of mitigation and adaptation actions. When taken together, climate services and climate assessment efforts result in more accessible information, data, and resources that are usable to decision-makers.

Assessments like the NCA are climate services that can inform decisions and actions in many ways, from providing direct access to localized data and mapping tools to building communities of networked experts. Participants in NCAs have long indicated that the relationships they build and the professional development gained over the course of being involved in the assessment process are often as valuable to them and their careers as the report content itself (Crimmins et al. In preparation).

This paper seeks to summarize and analyze the history and recent developments of the U.S. National Climate Assessment (NCA) to understand how:

1. Laws, regulations, and broader institutional implications impact what assessment developers must, can, and cannot do;
2. Creation and evolution of NCA has evolved and how it might continue to evolve to leverage future opportunities and serve future user needs;
3. Lessons learned developing NCA might inform other assessment efforts by documenting the choices and trade-offs (and the reasons behind them) that assessment developers must balance.

This paper covers processes specific to NCA and thus the advances described may be most relevant to future NCAs and other interagency assessments. However, there are tenets, if not specific rules or processes, that other governments or organizations developing assessments are navigating. For instance, this paper describes the steps NCA took to better meet the needs of the users of this report while adhering to federal rules (see Core Requirements section below). While the exact steps NCA5 took may not be necessary or feasible for state or local assessment developers or may look very different for national assessments outside the US (Weingartner et al. 2018), the larger question of how to better meet user needs is one that many report authors and developers continuously grapple with, as it is important to ensuring salience of any assessment.

2 Assessments led by the U.S. Global Change Research Program (USGCRP)

USGCRP-led scientific assessments have been a core, legally required responsibility of the program since its creation (USGCRP 2024b). The program and its participating agencies work together to collate knowledge from disparate sources within the broader scientific knowledge base, create a synthesized understanding, and provide decision-makers with an authoritative look at the current state of science.

The design of assessments led by the U.S. Global Change Research Program is guided by a number of laws and requirements informing the development process (Crimmins et al. 2024). Understanding these requirements is crucial to understanding what is possible and what is required when designing the development process. Innovation and advancements in the development process must still be within the bounds of those constraints. As will be discussed later in the paper, these requirements serve an important purpose in ensuring that program-led assessments are authoritative, trustworthy, transparent, and credible sources of scientific information.

Beyond those requirements, USGCRP products are subject to additional stipulations not inherent to assessments as a category of scientific work (Crimmins et al. 2024). One distinction for USGCRP-led assessments is that authors do not generally undertake any new, original research. While USGCRP and interagency working groups may develop technical inputs (such as Environmental Protection Agency's Climate Change Impacts and Risk Analysis report (EPA 2017) or National Oceanic and Atmospheric Administration's State Climate Summaries (Kunkel et al. 2022) or downscaled datasets for use in assessments (Basile et al. In preparation), authors typically assess only existing scientific information that meet information quality standards, rather than generating new knowledge (OMB 2019). While many assessments follow this model, some do not. For example, the California Climate Assessment has a statutory requirement to undertake original research in service of answering some California-specific questions that come up during the course of assessment (California 2018).

A second distinction is that USGCRP-led assessments are policy neutral. Policy neutrality is a core value of USGCRP products, which are developed with the intention of informing and supporting decision-making, not advocating for specific outcomes or actions (Crimmins et al. 2023). This distinction allows for the information in assessments to serve as the scientific foundation underlying the policy development process, while remaining separate from other complicated political, social, or economic factors inherent in prescribing policies, rules, or regulations. While policy neutrality is also a feature of assessment reports developed by the IPCC, other national or state assessments include policy analyses (e.g., cost-benefit evaluations) that support assessment recommendations (California 2018; UK 2022).

USGCRP has developed a number of different assessments looking at elements of global change including both the First and Second State of the Carbon Cycle Reports, as well as other climate related special reports on topics such as food (Brown et al. 2015) and human health (USGCRP 2016). However, for the purposes of this paper, we will focus on the National Climate Assessment, which is the most broadly known and highest profile product that USGCRP has produced (Fig. 1).

Fig. 1 Five NCAs have been published since 2000. Each report has documented the process by which that report was created, showing iterative evolution of both the report itself and the community that is brought together each cycle to build it

3 Background on NCA

The NCA is the government's premier report on the impacts, risks, and response to human-induced and naturally occurring climate change within the United States (Crimmins et al. 2023). It is a Congressionally-mandated quadrennial report, obligating USGCRP to undertake a periodic assessment of scientific knowledge to inform Congress and the Nation in determining responses to the threat of climate change (1990).

To date, there have been five NCAs published by the U.S. Government. Each NCA has incorporated advancements and lessons learned from the previous assessment, with a marked evolution of the report from the initial concept in NCA1 to the robust coverage of content in NCA5. Alongside the American public's increasing awareness of the climate change issue, the increasingly urgent need for climate information, and the natural growth over time of the number of people who have heard of or participated in an NCA (Chu In preparation), we posit that innovations throughout the NCA development processes have helped to strengthen the assessment's credibility, salience, and legitimacy, even as user needs evolve (Crimmins et al. In preparation). Efforts to make the report more useful, usable, and used aims to brings more users to the table, some of whom may then seek to engage and contribute in the next assessment cycle, thus creating a positive feedback loop that shapes future innovations in the NCA.

Iterative evolution is an inherent component of the NCA, but it also poses challenges. The increasing complexity of the report and its user base make the development process more nuanced and difficult to manage, especially within the time frame outlined by the GCRA and within other budget and staff constraints. Before describing some of the innovations in the assessment development process, we first describe these requirements and constraints. Additional details about the history of NCA can be found in the Supplemental Materials.

4 Core requirements of an NCA

Any NCA has some basic requirements that it must meet. These include foundational, and in many cases legal, obligations regarding content and process to which the NCA must adhere. In this section, we will walk through overarching statutory requirements, applicable guidelines and policies, and articulate how NCA complies with each through the development process.

4.1 The Global Change Research Act

The legal statute that both authorizes and requires creation of the NCA is found in the Global Change Research Act of 1990, Sect. 106 (1990). In sum, there are three basic technical requirements that the law says must be present in any NCA:

1) The NCA must "integrate, evaluate, and interpret the findings" of USGCRP. This includes discussing any scientific uncertainties in those findings.
2) The NCA must evaluate the effects of climate change on several specific sectors of the U.S.
3) The NCA must analyze trends in global change in various forms at specific time horizons: 25 years and 100 years into the future.

While the GCRA sets a baseline of the topics that must be included in the NCA, the way that baseline is met is left to USGCRP to determine. Since the first NCA was developed, it has been clear that NCAs are structured as narrative-style reports, with individual chapters covering individual topics of interest. Additionally, USGCRP has evolved a chapter structure over time that provides increased structure and guidance to authors to better standardize the report content in a way that helps users access and utilize the report (Crimmins and Avery 2023).

4.2 Highly influential scientific assessments

The U.S. Office of Management and Budget (OMB) defines "influential scientific information (ISI)" as any information that "will have or does have a clear and substantial impact on important public policies or private sector decisions" (OMB 2004). As a general rule, ISI is held to the standards established by the Information Quality Act (IQA) (2000) and must undergo a formal peer review process before it can be disseminated by the Federal Government. A highly influential scientific assessment (HISA) is a subset of ISI that "could have a potential impact of more than $500 million in any year, or is novel, controversial, or precedent-setting or has significant interagency interest" (OMB 2004). HISAs, including the NCA, are subject to additional peer review requirements that build upon those applicable to standard ISI.

4.3 Other laws applicable to NCA

In addition to the GCRA, the NCA must comply with all relevant laws and processes as outlined by the Administrative Agency overseeing the project. Some specific statues that NCA is obligated to comply with include:

- The Federal Advisory Committee Act (FACA).
- The Information Quality Act (IQA).
- The Foundations for Evidence-Based Policymaking Act (Evidence Act).
- The Copyright Act, and/or Intellectual Property (IP) requirements.
- The Paperwork Reduction Act (PRA).
- Federal Register Notices (FRNs).
- The Freedom of Information Act (FOIA).

Each of these statutes have direct impacts on how the NCA is developed and prepared. For example, FACA determines how the NCA author teams are structured, how clearances and public comments are overseen, and what limits on oversight are imposed on the FSC. Both IQA and the Evidence Act put significant obligations on authors to both ensure that the literature and data they take into their review meet quality standards sufficient to merit government usage of the underlying data, and that the technical inputs are publicly available for users of the report to vet for themselves the underlying technical information. Additional information on how NCA complies with these major statutes is included in the Supplemental Materials and in Crimmins et al. (2024).

4.4 Other laws and regulations impact how NCA materials are developed

Additionally, other laws and regulations place requirements on a project like NCA that shape it's final form and delivery. For example, NCA5 designed figures that use accessible color palettes to accommodate individuals with color vision deficiencies (i.e. color blindness) (Fig. 2), in part, because Sect. 508 of the Rehabilitation Act requires that all federal electronic resources be accessible to individuals with disabilities (Division 2020). Federal agencies and the government itself all have scientific integrity policies to which participants in the NCA must adhere. All participants in the NCA process have ethical conduct standards that are obligatory. USGCRP pioneered a Code of Conduct for NCA5, and all participants going forward will be required to comply. Additional information on these and other requirements on NCA participants can be found in the Supplemental Materials.

5 Additional requirements of an NCA

In addition to the legal requirements that all NCAs are statutorily required to meet, there are a number of *de facto* policies and guidelines that govern products of the scope, scale, and impact of an NCA, particularly if they are to be credible, legitimate, and salient assessments representing the views of the U.S. Government (Crimmins et al. In preparation).

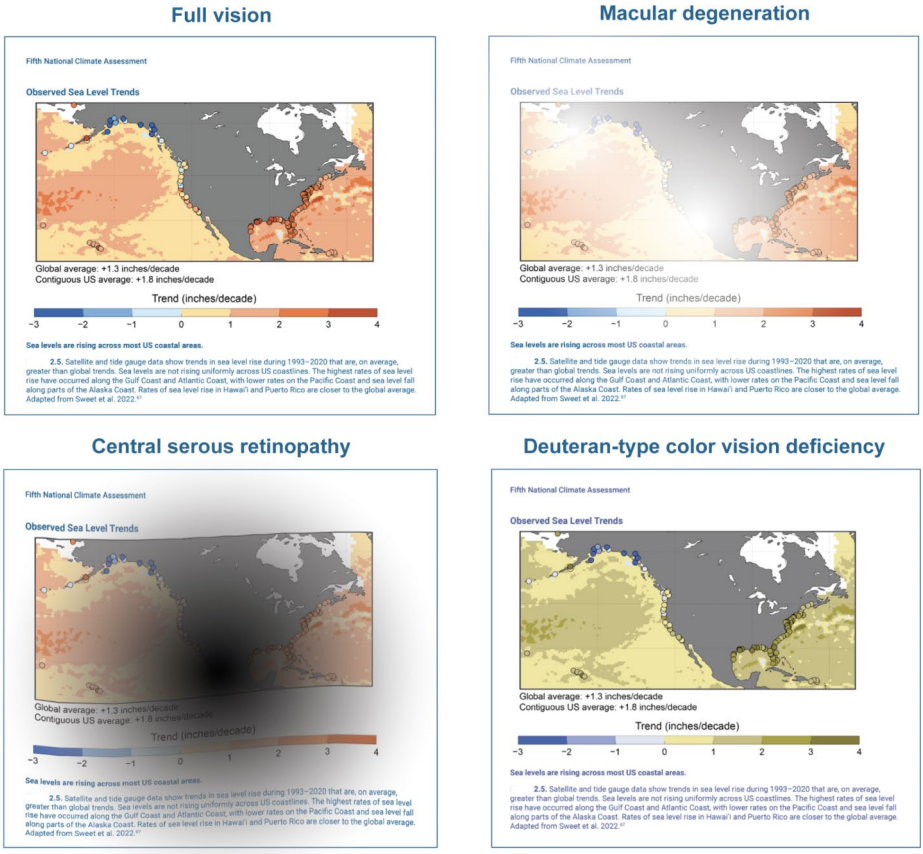

Fig. 2 Depiction of what individuals with full vision (top left) see when looking at a NCA figure compared to individuals with macular degeneration (top right), central serous retinopathy (bottom left), and deuteran-type color vision deficiency (bottom right). Visual impairments can reduce the readability of a document and are key considerations for designers when developing report elements, including figures, tables, color palettes, and fonts. NCA is designed to be 508-compliant and as broadly accessible as possible for individuals with these and other visual impairments

1) The NCA must be developed as written text but does not need to be delivered in the form of a printed report.

To be compliant with all the legal requirements previously discussed, the NCA must be developed in written format. Federal policies and laws around peer review and transparency in the assessment development process, including data management and evidence tracking, necessitate access to written or visual materials (e.g., figures or tables). In other words, NCA must be a written document at least at some stage in the development so that reviewers and public commenters have a common shared draft to review. Furthermore, copyright and IP ownership rules often presume the report being physical material of some form (Crimmins et al. 2024).

That said, NCA can be delivered in final form as something other than a printed report or book. In fact, NCA5, for the first time, delivered a website as the report of record, rather than a product designed for print. While websites were also built for previous NCAs, the printed reports were the legal reports of record delivered to Congress (Avery et al. 2018). Knowing from the beginning that the final product would be something users read on a screen affected the way authors thought about chapter structure.

2) The credibility and authoritativeness of an NCA hinges on its transparency.

Transparency is integrated into all stages of the NCA development process and is critical to ensuring report credibility and authoritativeness. Chapters are written with extensive input and participation from a wide range of scientists and experts, including multiple opportunities for public engagement. Figures are developed with an emphasis on traceability and reproducibility, including the documentation of complete and accurate figure metadata, use of publicly available datasets, and appropriate source attribution. Chapter text, figures, references, figure metadata, and Traceable Accounts are all publicly available in the final NCA product, and descriptions of the development process can be found in the report Appendices and supplemental materials. But the final assessment product that readers see belies the complex set of tools and processes required to ensure this level of transparency. Additional information about managing the complexity of an NCA in a transparent process can be found in the Supplemental Materials.

3) The NCA must meet the needs of the users of the report.

The GRCA does not explicitly define the *audience* for NCA. Legally, the assessment is directly delivered to Congress (1990), but it has always been the interpretation of USGCRP and OSTP that the report should be developed with the American public as the intended users of the report, a notion repeatedly echoed in public feedback (Cloyd et al. 2016; Avery et al. 2018; USGCRP 2022; Avery et al. 2023b; Crimmins et al. 2023). Identifying who uses the NCA, how they use it, or how the NCA might be altered to improve use has been an ongoing challenge. This has been in part due to the lack of opportunity and funding to conduct a formal use evaluation of previous NCAs, as well as regulations like the PRA and FACA (Table 2) that make it difficult to poll readers or conduct focus groups (NASEM 2024).

In the absence of formalized evaluation efforts, the NCA developers have long relied on public engagement and input from the USGCRP member agencies on their constituent's needs to inform author choices. NCA3 was overseen by a public federal advisory committee, which conducted public review and provided opportunities for engagement throughout the development of the report. NCA4 transitioned to a federal steering committee, but maintained the emphasis on public engagement with multiple federal register notices, author engagement events, and a NASEM peer review. Notably, NCA4 authors found the regional chapter's engagement workshops to be helpful in informing chapter scope. NCA5 expanded on this trajectory, creating more events for every chapter, more public reviews, and additional time for authors to engage with experts beyond their writing teams. More information on NCA's engagement efforts can be found in Lustig et al. in this issue (Lustig et al. In preparation).

Table 2 Description of the various laws, regulations, and government systems with which the NCA development process is required to comply. The major ways that NCA complies with each of these is noted

Statute/Function	What the statute requires	Why it applies to the NCA	How the NCA takes this into account
Global Change Research Act (GCRA) (1990)	Authorizes and mandates USGCRP to develop and distribute the NCA	Legal authorization & mandate for creation of the report	Creating the NCA with inclusion of mandated topics, time horizons, and uncertainty measures
Federal Advisory Committee Act (FACA) (1972)	Forbids U.S. Government (USG) agencies from receiving "consensus advice" from groups that mix Federal and non-Federal employees	Mixed author groups (both fed & non-fed authors together) are valuable to ensure the broadest possible set of knowledge present in the NCA	NCA chapter contributor structures are specifically designed to comply with this restriction (Avery et al. 2018)
Information Quality Act (IQA) (2000)	Requires USG agencies to verify the quality, utility, objectivity, and integrity of information they disseminate	The NCA is considered a "Highly Influential Scientific Assessment" (HISA) under OMB's IQA guidelines, triggering strict peer review and other required quality-control measures (Crimmins et al. 2024)	A designated federal IQA official ensures that the NCA meets legal requirements. USGCRP provides guidelines for ensuring sources for NCA meet IQA requirements. The NCA goes through multiple reviews through the public, agencies, and National Academies.
Foundations for Evidence-Based Policymaking Act (Evidence Act) (2018)	Requires public transparency about the evidence, including scientific information, that USG agencies use	Data, methods, information, etc. underlying the NCA must be publicly transparent	NCA develops operational processes for data management, and documentation and presentation of metadata
Copyright Act and/or Intellectual Property (IP) requirements (1976)	Copyright and patent law apply to all contributions to NCA content and materials	All NCA participants must have IP rights for their contributions waived to ensure open creative commons access to NCA materials (Crimmins et al. 2024)	For non-federal authors, General Counsel from the Administrative Agency works with authors to obtain statements from employers disclaiming IP
Paperwork Reduction Act (PRA)	Requires USG agencies to follow OMB processes before posing questions or gathering information from the public	The NCA process gathers information from authors and other participants who are not Federal employees	NCA staff and leadership must monitor NCA processes for any gathering of information that could trigger PRA restrictions, and secure waivers where needed
Federal Register Notices (FRN) (OMB 2022)	The Federal Register is the official record of announcements from USG agencies, used for official notice of planned actions	Announcement tool for calls for author nominations, notice of planned public engagement (legally required), and opportunities for public comment and review	USGCRP agencies and the NCA Administrative Agency develop, manage, and publish FRNs throughout the report development process
Freedom of Information Act (FOIA)	Requires release of USG agencies' information and communications, upon request, to the public	The NCA, like any government agency or project, may be subject to FOIA requests	Comply with FOIA requests, as well as proactively release information wherever possible and ensure disclosure of process materials, such as comment responses, upon report release

Until such an evaluation is conducted, report developers and authors are still limited in their understanding of how people have used previous NCAs. Because of this limitation and because user needs naturally evolve over time, public engagement opportunities during an NCA development cycle are some of the only opportunities for feedback (Lustig et al. In preparation). Based on public and NASEM input USGCRP has received on its products and activities, the NCA caters to a very broad audience (Avery et al. 2023b). In practical terms, this means making numerous process choices that ensure authors produce a product that is usable, including things like limiting report length, editing for clarity in writing, and budgeting time and resources to develop visually compelling graphics.

4) The NCA needs to meet the needs of the contributing agencies.

As one of the many audiences of NCA, the federal agencies that sit on the SGCR and fund USGCRP's work have direct interest in ensuring the NCA is useful to their programs and priorities. The driver of agency interests and priorities are often the same as USGCRP's: the needs of the audiences they serve. The fact that there is overlap between the communities that agencies serve and the users of NCA is one important motivational factor for federal agency participation in NCA development in the first place (Fig. 3).

As agency interests and needs have evolved and expanded, so too have the chapters and content expectations of the report expanded over time to meet those user needs. As more federal agencies continue to broaden their work in the climate space, join USGCRP to better coordinate that work across the government (DHS 2023; HUD 2023), and strive for co-production principles of considering and incorporating user needs, we expect this trend of expansion into new NCA content to continue. Additional discussion on the consequences of increasing report size can be found in the Supplemental Materials.

6 Innovations

Given the huge array of legal, policy, and other needs, NCA development has grown to become an incredibly complicated and intricate process. Navigating these difficult waters requires an understanding of the foundational history of NCA, a clear vision for each individual report's development process, and the ability to identify how new scientific information and process innovations can be built into the established assessment program.

Moreover, many of these innovations are focused on the fundamental difference between assessments and scientific literature: the audience. Building assessments to be transparent, readable, usable, and accessible to the audience is a critical part of assessment development. See Table 1 for more details.

6.1 Advancements in chapter format

6.1.1 Risk-based framing and key messages

A goal of any science assessment is to present the science in such a way that it best supports the needs of decision-makers. The way information is framed is well known to impact how users of that information interpret and utilize it (Kühberger 1998; Mishra et al. 2012;

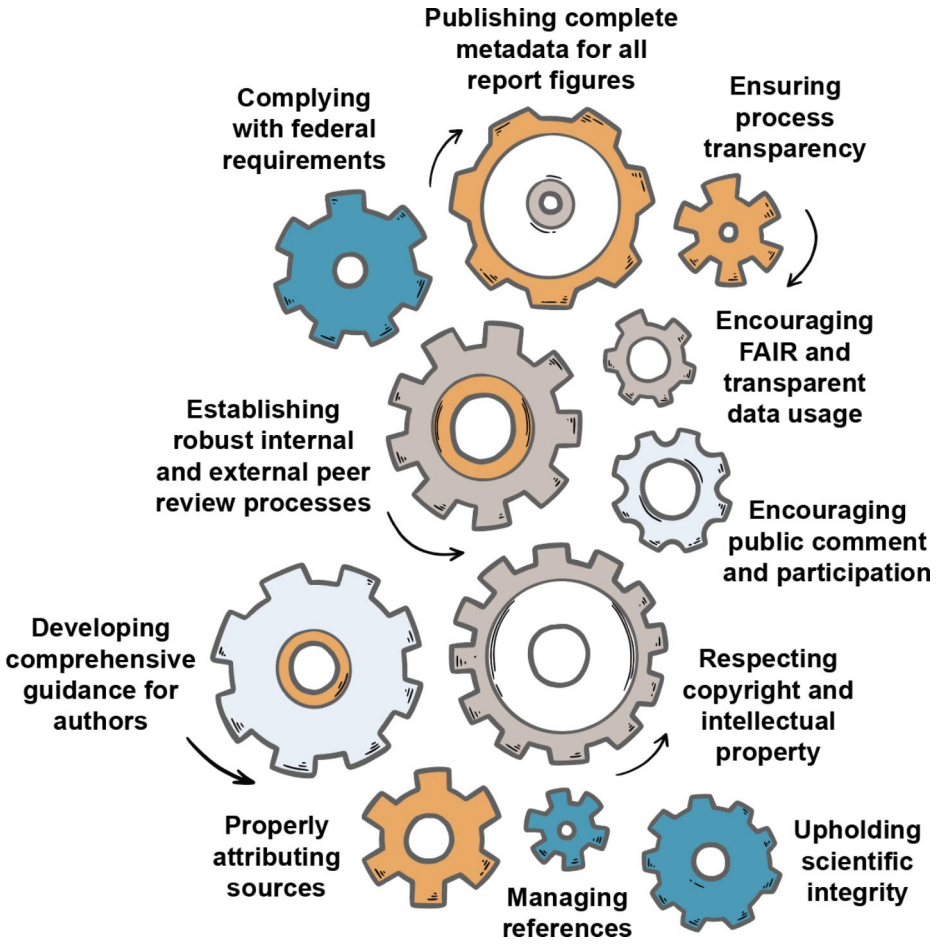

Fig. 3 NCA5, like multiple NCAs before it, is the culmination of years of process, documentation, review, and accessible design (Maycock 2023). Like the gears of a machine, these elements work together to create an interlocking and highly effective overall product. They require a vast array of data tracking and materials management that are essential for ensuring that the report is transparent, complies with applicable legal requirements, and reaches the widest possible audience (Maycock et al. 2023; Crimmins et al. 2024)

Melillo et al. 2014; Weaver et al. 2017; USGCRP 2018, Osaka et al. 2021; Crimmins et al. 2023). Based on feedback received during and after the development of NCA3 (NASEM 2016; Weaver et al. 2017), risk-based framing (RBF) was introduced in NCA author guidance. Authors are encouraged to focus on topics that entail potentially serious consequences to human and natural systems and seek to answer the question: *What is it you value that is at risk?* RBF helps authors identify the questions that users most need addressed, thus framing the scope of each chapter's content.

As described, RBF reflects a significant departure from typical technical research dialogue, which tends to follow a logical chain from cause to effect. The NCA emphasis on societal values speaks directly to a critical difference between assessments and scientific literature: the audience. Policymakers and decision-makers often come to decisions or actions

by first recognizing what is at risk, and then asking how they need to act to protect the thing they value that is under threat. RBF creates a system of shared language and framing between scientific information and decision-makers. Additionally, NCA5 authors use RBF to create a chapter structure to better support decision-maker needs. Authors use RBF to build out Key Messages, Traceable Accounts, and associated calibrated language.

Key Messages (KMs) are brief high-level statements used in nearly all assessments that capture the main takeaways from a section of a chapter. Because some readers will only read the KMs, they are critical for communication and dissemination. Therefore, the KMs are designed to be clear, unambiguous, and content-rich statements that convey a complete and accurate message without additional context needed (Avery et al. 2023a).

In recent assessments, public engagement efforts have helped authors understand user perspectives on what they value that is most at risk, aiding the authors in developing useful and usable content. USGCRP facilitates workshops, webinars, public comment efforts, and other engagement activities, such as conference presentations and Tribal consultations, to ensure public input shapes the scope of chapter content. Feedback received from both the NCA authors and audience suggest that such public engagement efforts have improved the readability and usefulness of KMs (Lustig et al. in preparation).

We anticipate RBF will continue to be used in future NCAs. The value it provides, especially in framing the conversation around the risks and impacts of climate change, is intended to focus readers on key issues and allow them to immediately glean the high-level takeaways. In this way, RBF moves the climate conversation towards action. That said, the science around the effect of framing on a reader's interpretation and use of information is progressing (Maxwell et al. 2022). We anticipate that future NCA leadership will continue to be responsive to public feedback as well as advances in science communication, evaluating whether RBF remains a useful approach and determining when to change tack if better approaches arise. In addition, use of RBF need not be limited to KMs and Traceable Accounts, but may also be a useful framing for chapter content, as well as communication and outreach when the assessment is released. Additional detailed discussion on RBF and its use in assessment can be found in the Supplemental Materials.

6.1.2 Traceable accounts & calibrated language

Another structural tool used in assessment chapters to improve usability is Traceable Accounts, which document the author's decision-making process when developing and framing their chapter. Building on an initial concept developed for the IPCC (Mastrandrea et al. 2010) and subsequently optimized by USGCRP for the NCA, Traceable Accounts serve as a tool for authors to "show their work" more explicitly (Chang 2023). Rather than repeat the assessment results discussed in the main chapter text, Traceable Accounts describe *why* authors came to those conclusions. These sections describe the quantity and quality of information sources, the level of agreement among evidence used, and how confident the authors are in the state of knowledge. This includes author choices around the question "*What do you value that is at risk?*"

In addition to explaining their decisions to highlight specific risks, authors are also required in the Traceable Accounts to explain the decisions made in choosing the calibrated language used in their Key Messages. Calibrated language is defined as "the use [in scientific assessments] of specific terms to express degrees of confidence and likelihood [of a

given relationship or outcome]" (Crimmins 2020). Use of Traceable Accounts and calibrated language began in a formalized way in NCA3 and consistent application has improved in assessments over time. In recent assessments, each Key Message has an associated Traceable Account and authors are use them to document their choices, including the evidence supporting calibrated language choices. Unlike previous NCAs, which used a simplified list of terms, Volume I of NCA4 (Climate Science Special Report) and NCA5 adopted the full set of calibrated terms used in the IPCC Fifth Assessment Report (Mastrandrea et al. 2011). In Volume II of NCA4, calibrated language was shown only in the Traceable Accounts, to improve the readability of the Key Messages within the chapter. However, NCA5 integrated calibrated language into each sentence or phrase of the chapter Key Messages. This was done in part with the hope that confidence and likelihood values would be maintained when Key Messages are quoted by users (Painter 2013; Collins and Nerlich 2016). This helps ensure the proper context and certainty in assessment statements are conveyed by secondary communicators. Increasing visibility of these terms may have the effect of normalizing use and improving understanding of calibrated language.

Evaluating confidence and likelihood is a key part of the assessment process and a requirement of assessment authors, further differentiating the development of scientific assessments from other types of technical publications (Table 1). Traceable Accounts and calibrated language form a critical part of the traceability, transparency, and credibility of an NCA. The importance of NCAs clearly and directly connecting these two elements with the Key Messages, which are likely the most widely read parts of the report, is significant. Taken together, these form the critical basis of authors' assessment work, taking in the broadest possible breadth of knowledge and distilling it to clear actionable messages. By describing the decision-making process and effort behind the development of these messages and making clear the level of certainty in the science, assessments allow readers to understand the deeper context behind the author's conclusions, as well as to check their work. Future NCAs should continue to refine this effort, including more efforts to help authors provide consistent information over time, as well as the metrics they use to come to their conclusions. The continued use and improvement of calibrated language across NCAs helps identify research gaps (Basile et al. 2023) and also provides an opportunity for agencies to evaluate how scientific understanding of specific topics has advanced over time.

6.2 Moving beyond a book

One of the most important advancements of NCA has been the transition away from a product designed to be printed and bound. For NCA5, the website itself is the official report of record, delivered to Congress to meet the GCRA. The delivery of NCA5 as a website is the culmination of groundwork laid by earlier NCAs. The NCA has long pioneered effective, web-based communication to aid readers in finding the information they are seeking, particularly as each successive assessment has grown larger. NCA3, at the time of its publication, provided the entire report in web form, with improved functionality over the more static NCA1 and NCA2 sites. The websites for NCA4, NCA5, and other USGCRP special reports benefited from continuous advancements in user interface and user experience design. The digital tools tested and pioneered in earlier iterations of the report live on today and continue to be the foundation of future innovation.

Delivering a website as the report of record allows for more flexibility and easier compliance with recent laws on evidence tracking and digital accessibility. For example, the websites for the last three NCAs have allowed users to view graphics metadata alongside each figure, providing direct connections between underlying data and the visualizations in the report. Similarly, NCA5 provides alternative text alongside every image in the report for the first time, providing improved access for those using screen readers (Avery et al. 2023a). Responsively designed website architecture can also make reports functional across different media platforms and tools (e.g., computers, tablets, phones).

The impact of the NCA5 website being the report of record had fundamental ramifications for report development right from the start. For instance, the NCA5 Overview authors intentionally developed the chapter with sub-headers conveying complete messages, wrote the text in short paragraphs, placed longer content in lists or tables, and incorporated photo collages related to climate impacts to improve navigation and visual interest for scrolling readers (Jay et al. 2023). Web interfaces were designed to be dynamically responsive to many different viewing tools. Search bars, cross-chapter links, linked definitions of technical terms, and other navigation tools allow readers to rapidly find content that is most interesting and relevant to them, without having to read the assessment linearly. These types of considerations are directly in line with the goals and principles set out by NCA5 leadership (Crimmins et al. In preparation).

Future NCAs should prioritize digital delivery systems and incorporate user experience design to meet evolving user needs. Decision-making requires more than just good information; it requires that information to be provided to users in a way that enables and empowers use of that information. Taking advantage of modern tools to deliver a web-based NCA that provides both information and a platform to help support individual choices is critical for broad accessibility. Such practices should be cultivated in future NCAs. Future assessment developers may also consider use of other multimedia tools and communication platforms to meet the evolving needs of users (see Crimmins et al. in preparation).

6.3 Sustained assessment

In its 2012 strategic plan (USGCRP 2017), USGCRP listed Sustained Assessment as a core programmatic goal. The idea behind sustained assessment was to move away from the development of singular products or events that placed heavy burdens on the research community and towards an ongoing process that supports continuous development and delivery of timely information in support of decision-making. In 2013, the National Climate Assessment and Development Advisory Committee released a report describing the concept of sustained assessment. This report went into detail about the purpose of sustained assessment efforts and provided a roadmap of conditions and efforts that would be necessary to achieve the vision set out in USGCRP's strategic plan (Buizer et al. 2013).

In concept, sustained assessment has strong merit. In addition to better serving the goals of the GCRA overall, it could provide better engagement between the users and the producers of assessment products. Sustained assessment would theoretically address engagement challenges by delivering steadier streams of timely, tailored climate information. In practice however, it has proven both logistically and practically challenging for USGCRP to fully embrace the sustained assessment approach described by Buizer et al. (2013).

Quadrennial assessment reports are high effort projects; they require a great deal of time, work, and care to be done well and to deliver useful products. Since NCA2, development cycles have mostly aligned with the prescribed four-year time cycle identified in the GCRA (Fig. 1). To accommodate the high level of effort required, the next NCA must begin development before the previous one is fully finished; this expansion of the overall time frame for report development has helped reduce the boom-bust nature of early NCA assessment efforts.

This ongoing cycle has resulted in continuous development of NCA products, which means a continuous cycle of assessment activities for the scientific community, USGCRP agencies, and assessment staff. One benefit of this is that it creates an ongoing assessment project that addresses the concerns previous cycles had about intermittent engagement or boom-bust cycles. However, this overlap also has the potential to leave less room and fewer resources for consideration of additional assessment products, like a topically focused special assessment report. The last special report released by USGCRP was the second state of the carbon cycle report in 2018. No other special report announcement has been made at this time.

Much of the expansion of activities that might fall under the concept of sustained assessment has been led by state and local entities rather than USGCRP. Many states and municipalities are developing assessments around climate vulnerability, risk, and response (California 2018; Adams et al. 2021; Wisconsin 2021; Mathews et al. 2024). Some of these assessments rely on the NCA as an input to their work, connecting the national effort to local needs. One benefit to this bottom-up sustained assessment approach is that there is a growing cadre of climate assessment experts in the country with deep expertise in their own local area. This increase in expertise across the U.S. is a positive development, as future climate decisions will be increasingly tied to highly localized needs (Moss et al. 2019).

Additionally, the rise of climate services points to a change in how the scientific community might think about assessments, from a single standalone product to one piece in a portfolio of tools. Other climate services beyond assessment reports, such as climate indicator dashboards and interactive online mapping tools, may be able to publish up-to-date climate data in between the release of NCAs. This type of timely access to climate information speaks to the "sustained" element if not the "assessment" element of the original concept, providing people with data needed to make actionable decisions. These tools can also serve to inform the NCA authors as they are developing the next report. The current USGCRP Strategic Plan incorporates many of these lessons as the Program looks to future work (USGCRP 2022).

6.4 Evolving knowledge and expertise

As climate-related scientific knowledge and user needs have evolved, relevant topics of scientific interest (for example, beyond just Earth science) and different forms of knowledge (for example, beyond just peer-reviewed literature) have become critical inputs to the NCA, with direct impacts on development processes (Crimmins et al. in preparation). Two examples of how evolving knowledge and expertise have been included in NCAs are described below.

6.4.1 Indigenous knowledge

Indigenous Knowledge (IK) systems have been included in NCAs since NCA1 (STAC-CWG 2021), and all NCAs except for NCA2 have included a standalone chapter dedicated to Indigenous peoples (Whyte In preparation). Indigenous representation has grown over time: NCA4 saw much more extensive participation from Indigenous scientists on a wide variety of topics throughout the report. No longer limited to a single chapter, Indigenous science topics were included across the assessment, especially throughout the regional chapters, which brought greater visibility to Indigenous communities across the country and highlighted regionally distinct impacts. Also, during NCA4, approximately 50 authors worked together to establish a list of IK-related terminology that was shared with chapter teams in an effort to ensure consistency across the report. NCA5 established the terminology list as formal author guidance and made strides in ensuring that Indigenous scholars led the development of Indigenous content across the report (Grade et al. 2023).

NCA5 not only advanced inclusion of IK in the report content itself, but also in the assessment development process. In 2022, the White House Office of Science and Technology Policy hosted several formal Tribal consultations on the inclusion of IK in federal science (CEQ 2022). USGCRP participated in these consultations to learn how the NCA could better incorporate IK. The consultations resulted in revisions to the NCA Information Quality Act guidelines (Crimmins et al. 2024), which determine the source material that can be used in the assessment. The updated guidelines explicitly lay out principles for including IK and served to make way for the broader inclusion of IK across the report (Avery et al. 2023b).

6.4.2 Social science

The social sciences have been increasingly integrated into the NCA over several report cycles (Maxwell et al. 2022), and the value of multidisciplinary representation has been recognized in a number ways: The USGCRP 2012–2021 Strategic Plan highlighted the social sciences as critical to holistic scientific assessment (USGCRP 2022). Multiple reviews by the National Academies of Science, Engineering, and Medicine (NASEM) of NCAs and other programmatic work have highlighted and pushed for inclusion of social sciences (USGCRP 2013, Weaver et al. 2014). The USGCRP Social Sciences Task Force– a precursor to the current USGCRP Social Science Coordinating Committee (SSCC)– was established to bring organization and rigor to the incorporation of social science knowledge across the Program's work. After NCA4, the SSCC hosted a series of focus groups conducted with report authors and subsequently developed recommendations for the further integration of social science topics into future National Climate Assessments (Maxwell et al. 2022). The group followed up with a memorandum to the NCA5 Federal Steering Committee that ultimately led to the creation of the new NCA5 Social Systems and Justice chapter (Marino et al. 2023).

The SSCC also shared opportunities for public participation and input on NCA5 with the broader social sciences community, reaching out through professional societies and personal networks. In October 2020, they hosted a public webinar targeted at the social science community that outlined the various pathways for participation in the NCA5 development process. The SSCC outreach efforts were targeted and specific, aimed at introducing the

NCA to a relatively new audience, addressing concerns around interdisciplinary collaboration, and demonstrating the role that social sciences have to play in the NCA. Their outreach resulted in a large increase in the number of social scientists who volunteered as authors– in the Social Systems and Justice chapter, but also across the entire assessment.

The Social Systems and Justice chapter takes a novel approach to its framework, which can be used by other chapters to inform their social science content in the future. Rather than grounding their chapter in risk, the Social Science and Justice author team branched out to address topics such as the social processes that shape carbon emissions, the role of governance and policy processes in determining social outcomes, differences in ways of knowing and understanding climate change, and the characteristics of a just transition. Across the assessment, the increase in social scientists likely helped advance coverage of scientific information on environmental justice, which was a new area of emphasis for NCA5 (Mendez et al. In preparation).

Expanding the knowledge base of NCAs requires three things: (1) sources of high quality scientific information relevant to climate change to assess, (2) a scientific community willing to serve as authors and technical contributors on those topics, and (3) the will to expand the assessment into new knowledges, particularly among assessment leadership and USGCRP agencies. The first and second requirement were met for both IK and Social Science for many years. But it can take time to meet the third requirement, often longer than one NCA cycle as evidenced by the multi-year effort to include a chapter on Social Science and Justice. Expansion of future NCAs into evolving knowledge bases will likely continue to be an area of evolution for USGCRP, and will also depend on other external factors, such as future administration priorities and agency resources.

7 Conclusion

Since first created under the GCRA, the National Climate Assessment has evolved into a critical tool supporting climate change related policy choices throughout the United States. While developed by the federal government, the audience that both uses and relies on the NCA has grown far beyond the federal agencies that help govern and construct it. NCA5 saw the largest group of people in history come together to build the report, with at least one rough estimate of over 5,000 individual participants (Crimmins and Avery 2023). Feedback from authors and other participants make clear that a core value-add to NCA participation is the integration into a community of experts across disciplines that don't easily and naturally collaborate. Participants have reported that this interdisciplinary relationship building is a core part of why many found the experience to be positive and valuable (Avery and Crimmins 2022).

As the state of climate knowledge continues to grow, the NCA is well-positioned, through both process and statute, to grow with it and continue to meet its stated goals: assisting the Nation and the world in understanding, assessing, predicting, and responding to global change. Even with all the established rules and other policies and guidelines, NCA has not withered, nor has it remained stagnant. Within these constraints, and even as new obligations have been put upon the developers of the report, NCA has evolved and continues to strive towards building a better product.

The authors anticipate that future NCAs will continue to evolve to meet changing legal requirements and shifting user needs. As new scientific information becomes available and users face varying climate risks, there will be pressure to include new topics within the scope of future assessments. Conversely, other topics, particularly where science is "settled" and few edits or updates would be required, may fade in visibility or be removed from future assessments. Efforts by USGCRP to move into a long-desired evaluation space indicate that future efforts to quantify impacts of assessments like the NCA will remain a priority for USGCRP, such that evolving user needs can be considered early in assessment planning cycles (NASEM 2024).

Other products or technical inputs may be created as separate efforts are needed to explore specific topical areas in depth. Completely new assessments may be identified and grow in importance, like the National Nature Assessment. New tools, such as the NCA Atlas, will likely continue to emerge as critical methods by which assessment content can be delivered to users to support decision-making. With these evolutions to meet the needs of the moment, we anticipate that the NCA will continue to be a critical tool for communication, decision support, and scientific inquiry.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10584-024-03854-8.

Acknowledgements Authors would like to acknowledge editorial and technical support from the North Carolina Institute for Climate Studies, especially Tom Maycock, Andrea McCarrick, and Jessicca Allen. Authors also acknowledge Kate Bucacink and the National Oceanic and Atmospheric Administration's General Counsel for helping build the legal requirements list shown in Table 2 in the Supplemental Materials.

Author contributions All authors contributed to the development and direction of this paper. Material preparation, information collection, and analysis were done by all authors. The first draft of the manuscript was written by C.W.A. and all authors helped revise iterative versions of the manuscript. Graphics were prepared by A.D.L. All authors read and approved the final manuscript.

Funding This work was done during the authors employment and is topically connected to their responsibilities therein. As a relevant action of their employment, no additional funding was used or needed beyond normal activities to generate this work. The authors declare that no funds, grants, or support beyond what is described here was received during the preparation of this manuscript.

Data availability No original datasets were generated or used in this paper. All referenced datasets are linked and available in reference lists.

Declarations

Competing interests C.W.A., A.R.L., A.G., C.R.L., and I.F. are all employees of ICF, a consulting firm who provides staffing to support USGCRP. Their employment is in part to provide staff support to the development and publication of NCA. A.D.L. is employed by North Carolina State University to work at the North Carolina Institute for Climate Studies, a consortium with NOAA and NCSU to provide a Technical Support Unit for climate research and assessments. A.R.C. served as the Director of NCA5. D.B. is a federal employee of the National Oceanic and Atmospheric Administration in the Climate Program Office, which provides funding in support of USGCRP and the NCA. A.R.C. and D.B. also both served on the NCA5 Federal Steering Committee. The authors do not consider service in these positions to be competing interests and have no relevant financial or non-financial interests to disclose.

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