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FOCUS ARTICLE

Overcoming early career barriers to interdisciplinary climate change research

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Climate-change impacts are among the most serious and complex challenges facing society, affecting both natural and social systems. Addressing these requires a new paradigm of interdisciplinary collaboration which incorporates tools, techniques, and insights from across the social, natural, and engineering sciences. Yet, a wide range of intrinsic and extrinsic hurdles need to be overcome to conduct successful, integrated interdisciplinary research. The results of a bibliometric analysis and survey of early to mid-career scientists from 56 countries who were involved with the interdisciplinary DISsertations initiative for the advancement of Climate Change ReSearch (DISCCRS) emphasize the particular challenges faced by early career researchers. Survey respondents perceive conflict between the need for interdisciplinary climate-change research and its potential detriment to career advancement. However, participation in interventions for early career scientists, such as networking and training symposia, had both perceived and measurable impacts on the likelihood of engagement in climate-centric interdisciplinary research. Respondents also ranked alternative mechanisms for encouraging incorporation of interdisciplinary science at early career stages, prioritizing funding of interdisciplinary seed grants, fellowships, and junior faculty networks, interdisciplinary teamwork and communication training, and interdepartmental symposia. To this we add the suggestion that interdisciplinarity be incorporated into tenure and promotion evaluations through the use of exploratory science mapping tools. Despite the need to foster interdisciplinary research and the availability of multiple prospective solutions, there remain expansive structural challenges to its promotion and recognition which, unless collectively addressed, will continue to hinder its potential growth and application to climate-change science.

This article is categorized under:
Social Status of Climate Change Knowledge > Knowledge and Practice
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bibliometrics, early career, interdisciplinary

1 | INTRODUCTION

Interdisciplinary research (IDR) is commonly driven by an orientation toward addressing problems, spurring innovation, and tackling societal challenges that require fundamental knowledge from multiple disciplines (National Research Council (NRC), 2014). Given this approach, individual contributions may still fall within a single discipline, but the research, as a whole, is

interdisciplinary and collaborative. Such work is defined by overarching questions and themes which can only be addressed in an interconnected way. The growing importance of such an approach to scientific research is highlighted in the recent NRC report (NRC, 2014) and the identification by the National Science Foundation's (NSF) of so-called Convergence Research (a subset of IDR characterized as a truly integrated "process for catalyzing new research directions and advancing scientific discovery and innovation") as one of its "10 Big Ideas" for future research investments (NSF, 2016).

The development of IDR teams capable of integrating across broadly distributed fields has been shown to be beneficial for generating new research avenues and challenging established beliefs (Barry, Born, & Weszkalnys, 2008; Horwitz, 2003; Slater & Hearn, 1996), enhancing creativity and fostering innovation (Heinze, Shapira, Rogers, & Senker, 2009; Hemlin, Allwood, & Martin, 2004), and problem solving (Page, 2007), particularly across complex, socially relevant challenges (Gibbons et al., 1994; Lowe & Phillipson, 2009; NAS, 2004). Furthermore, IDR plays a fundamental role in fields that require scientific knowledge and management strategies drawn from tools, techniques, and insights generated across the social, natural, and engineering sciences. For example, climate change poses some of the most serious and complex challenges faced by both the scientific community and global society, and requires societally relevant, beneficial, and sustainable solutions. Relevant fields of science applied to this problem include, but are not limited to, physical climate dynamics, biological and ecological impacts, risk perception and assessment, adaptation planning, development, economics, engineering solutions, and policy analysis; none of these can tackle the problems of climate change through a siloed, mono-disciplinary approach. As such, the study of climate change and its impacts is, by its very nature, discipline-spanning, and thus may benefit most from integrated, team-oriented scientific approaches.

However, the pursuit of IDR can suffer from a range of barriers and costs (Table 1) which make it a substantially more challenging proposition than traditional, disciplinary physical/social scientific endeavors. These can be particularly challenging during early career stages, defined here as the period following completion of a doctoral degree and prior to tenure or tenure-equivalent promotion. Fewer untenured (unpromoted) scientists are engaged in IDR as compared to more senior colleagues, likely reflecting the premium placed on disciplinary intellectual output by the traditional academic structure (Carayol & Thi, 2005). Despite the penalty often associated with IDR during the tenure and review process (Lattuca, 2001; NAS, 2004; van Rijnsoever & Hessels, 2011), greater professional freedom, publication history, and experience enable tenured faculty to navigate the obstacles more successfully (Rhoten & Parker, 2004). Thus, while promotion and tenure provide a measure of academic job security to engage in IDR, there remain acute barriers which make more challenging the pathway to tenure for researchers highly engaged in IDR; this has been referred to as the "IDR paradox" (Heberlein, 1988). Nonetheless, early career scientists are likely to be as, or more, open to interdisciplinarity—particularly in the field of climate change—than their senior colleagues, because, with the growth of interdisciplinary departments, centers, and graduate programs, they are more likely to have been educated in an interdisciplinary culture (Milman et al., 2017). Indeed, younger faculty and graduate students express greater enthusiasm for IDR, and claim more experience and collegial connections in interdisciplinary contexts than do the senior colleagues (Rhoten, 2004; Rhoten & Parker, 2004). Yet, despite this strong start toward IDR profiles, they are also likely to identify and experience the potential costs and obstacles to employment and tenure associated with this track.

Here, we briefly review some of the major developments which have allowed for the expansion of interdisciplinary climate-change research, and created incentives for scientists to engage in IDR during early career stages. We then present a case study—using methods which are themselves interdisciplinary—focused on the impacts on recent PhD graduates with self-expressed interest in interdisciplinary climate-change research of an immersive, week-long symposia focused on team/collaboration training, science communication, and professional development. Our methods couple detailed bibliometric analysis, quantitative/qualitative survey analysis, and crowd sourcing of recent PhD graduates with self-identified interest in interdisciplinary climate-change research. Building upon this, we review the suite of intrinsic and extrinsic challenges to engag in interdisciplinary climate-change research, with a specific emphasis on those perceived challenges highlighted by our target population of early to mid-career social and natural scientists. Finally, we use the results from our case study to demonstrate the role of specific training and support in the promotion of interdisciplinary science, and—based largely on crowdsourcing among early to mid-career researchers—propose solutions to promote interdisciplinary climate-change research among early career physical, biological and social scientists, and engineers.

2 | RECENT EXPANSION OF INTERDISCIPLINARY CLIMATE-CHANGE RESEARCH

While interest in the vagaries of weather and local climate are likely as old as humanity, an appreciation for the roles of carbon dioxide and human activities on climate, and research into the Earth as an interconnected system, are quite recent (see Mooney, Duraiappah, & Larigauderie, 2013; Weart, 2013). In particular, the last two decades have witnessed an accelerating trend in climate-change research in general, and interdisciplinary climate-change research specifically. This work is driven by a combination of: (a) basic researchers dedicated to concerns about the environment recognizing that the majority of solutions

TABLE 1 Literature review of common challenges to interdisciplinary research

Concept	References
Extrinsic systemic barriers imposed upon Enterprise of IDR	
Perception: Institutionalism of science along disciplinary lines; peers retain incomplete understanding/respect of, or discrimination against, other disciplines or IDR; IDR associated with intellectual fads or research-lacking substance	Bergmann et al. (2005); Lau and Pasquini (2008); Leavy (2016); Milman et al. (2017); NAS (2004); Rafols, Leydesdorff, O'Hare, Nightingale, and Stirling (2012); Rhoten (2004); Slater and Hearn (1996)
Assessment: Focus on applied issues decreases perceived scientific rigor of study; IDR risky, poorly defined, or variable in terms of interdisciplinary integration; unclear or insufficient interdisciplinary accomplishments, contributions, or integration; strength of work due to its interdisciplinarity ignored; reviewer bias against, or lack of understanding of, IDR or methods/theories of other disciplines	Campbell (2005); Carayol and Dalle (2007); Carayol and Thi (2005); Hartesveldt and Giordan (2008); Klein (2008); Langfeldt (2006); Lau and Pasquini (2008); Laudel and Origgi (2006); Milman et al. (2017); Nightingale and Scott (2007); Öberg (2009); Pooley, Mendelsohn, and Milner-Gulland (2014); Rhoten and Pfirman (2007); Rinia, Van Leeuwen, Van Vuren, and Van Raan (2001); Sanz-Menéndez, Bordons, and Zulueta (2001); Slater and Hearn (1996)
Funding: Funding limited and/or defined through exclusion from "core" science; constraints imposed by research motivation in response to interdisciplinary requirement: Prohibits organic development of research concepts/questions	Bromham, Dinnage, and Hua (2016); Campbell (2005); Fox et al. (2006); Heberlein (1988); Salazar, Lant, Fiore, and Salas (2012); Slater and Hearn (1996)
Publishing: Disciplinary mandate of most journals can lead to publishing of IDR in journals with limited disciplinary readership; fewer citations of IDR papers in short term; slower publication of IDR	Bruce, Lyall, Tait, and Williams (2004), Campbell (2005); Heberlein (1988); Jacobs and Frickel (2009); Lau and Pasquini (2008); Levitt & Thelwall, 2008; Milman et al. (2017), Mitchell and Weiler (2011); Pfirman & Martin, 2010; Pooley et al. (2014); Rafols et al. (2012); Slater and Hearn (1996)
Structural: IDR poorly defined; successful IDR can lead to creation of new disciplines, and are thus no longer IDR; challenge for IDR to be socially relevant yet advocacy/value free	Fox et al. (2006); Lau and Pasquini (2008); Pooley et al. (2014); Slater and Hearn (1996)
Extrinsic systemic barriers imposed upon individual IDR researcher	
Education and training: Insufficient training in, early exposure to, opportunities for, and encouragement toward IDR; institutional uncertainty regarding appropriate level of, and methods for, student IDR training	Carayol and Thi (2005); Fox et al. (2006); Heberlein (1988); Salazar et al. (2012)
Research assessment: Institutional disciplinary research reward structures lead to view that IDR activities are extracurricular (post-tenure) activity that dilutes core disciplinary expertise; difficult to assess contributions to IDR given complex project management and authorship across disciplinary and IDR journals	Campbell (2005); de Boer (2006); Fox et al. (2006); Heberlein (1988); Lattuca (2001); Lau and Pasquini (2008); Milman et al. (2017); NAS (2004); Rafols et al. (2012); Slater and Hearn (1996)
Career placement: Departmental hiring places premium on disciplinary science; IDR focus more likely to lead to short-term employment (e.g., postdoctoral position), rather than tenure-track jobs; possible near-term income risk	Borrego and Newswander (2008); Hanks and Kniffin (2014); Millar (2013)
Career advancement: Discouragement of applied problem solving; IDR viewed as less rigorous: Leads to difficulty in obtaining tenure, research funding, publications, mentorship, and professional recognition; review committees view only disciplinary efforts as leading to promotion; scientists outside of core discipline do not serve on review committees or as invited letter writers	de Boer (2006); Golde & Gallagher, 1999; Fox et al. (2006); Heberlein (1988); Kniffen and Hanks (2013); Lattuca (2001); Levitt and Thelwall (2008); Milman et al. (2017); NAS (2004); Pfirman and Martin (2010); Rafols et al. (2012); Rhoten and Parker (2004); van Rijnsoever and Hessels (2011)
Intrinsic barriers to IDR	
Organizational: Contributions from different groups not interconnected; requirement for higher initiation effort/time; difficulties in identifying best collaborating scientists from different discipline, and managing coordination/integration of distributed knowledge	Carayol and Thi (2005); Heberlein (1988); Pooley et al. (2014); Milman et al. (2017); Rafols et al. (2012); Salazar et al. (2012); Slater and Hearn (1996)
Conceptual framework: Research motivated in response to interdisciplinary requirement is constraining: Prohibits organic development of research concepts/questions; IDR overwhelms fundamental research questions and/or disciplinary outcomes; limited movement of information between disciplines; poor definition of concepts across disciplines and spanning variable spatial/temporal scales and quantitative/qualitative data and models	Campbell (2005); Fox et al. (2006); Heberlein (1988); Pooley et al. (2014); Slater and Hearn (1996)
Disciplinary balance: Incomplete/delayed integration of social science into problems and projects leads to natural/social science power hierarchies; social scientists engaged in outreach components or to change behavior of target audiences and thus excluded from planning and core science	Campbell (2005); Fox et al. (2006); Pooley et al. (2014)
Internal communication: Lack of common vocabulary, concepts, mental framework, temporal/spatial scales of study, and methodologies	Fox et al. (2006); Füssel (2007); Lau and Pasquini (2008); Milman et al. (2017); Pooley et al. (2014); Salazar et al. (2012); Slater and Hearn (1996)
Dissemination: Need for both disciplinary and IDR publication; lack of clarify regarding authorship; differing expectations about publishing across disciplines	Campbell (2005); Mitchell and Weiler (2011)

exist at the intersection of science and society; (b) communication-focused academic and private-sector initiatives (e.g., Golde & Gallagher, 1999; McCright, O'Shea, Sweeder, Urquhart, & Zeleke, 2013); (c) institutional-level funding of interdisciplinary fellowships and research positions; (d) the development of interdisciplinary departments, schools, and centers within institutions to IDR; and (e) an apparent trend among many funding agencies toward interdisciplinary initiatives (Fox et al., 2006; Heberlein, 1988;). One tangible result of this shift in focus is the nearly exponential growth in the number of interdisciplinary climate-change publications (Xu, Goswami, Gulledge, Wullschleger, & Thornton, 2016).

At the individual level, basic researchers dedicated to concerns about the environment and the need to be advocates at the intersection of science and society (e.g., James E. Hansen of Columbia University, Jane Lubchenco of Oregon State University, Elinor Ostrom of Indiana University [deceased], Stephen H. Schneider of Stanford University [deceased]) have been outspoken advocates of interdisciplinary scientific approaches to climate-related issues of pressing societal concern. Likewise, education-focused initiatives that encourage innovation and cross-disciplinary understanding among future academics and the private-sector workforce can lead to more effective public communication, specifically in relation to cross-disciplinary impacts of climate change (e.g., Golde & Gallagher, 1999; McCright et al., 2013).

At the institutional level, the trend toward IDR can be seen in the funding of interdisciplinary postdoctoral fellowships and permanent research positions, and in the merging of traditional disciplinary departments into interdisciplinary departments. For example, the field of Geosciences has undergone a shift in which departments have been reorganized and/or departmental names containing words such as "Geology" or "Geological" have been replaced by more broadly encompassing terms such as "Earth" and "Environmental"; in the last few years alone such reorganization has occurred at diverse institutions including Stanford University, Michigan State University, and Boston University. These changes reflect a broader view of the diversity of expertise required to understand and combat climate change, as well as, in some cases, enhanced integration of the social and natural sciences. Elsewhere, IDR is promoted through the development of schools and centers within institutions to promote interdisciplinary approaches to climate-change research. Examples include the Pennsylvania State University Earth System Science Center (1986), Duke Nicholas School of the Environment (1991), Tufts Global Development and Environment Institute (1993), Princeton Environmental Institute (1994), University of North Carolina Coastal Studies Institute (2003), Carnegie Mellon Steinbrenner Institute for Environmental Education and Research (2004), and the Stanford Woods Institute for the Environment (2004).

Scientific fields such as Conservation Biology and Ecology have long recognized the role of IDR in addressing complex problems, as well as the challenges posed by such research (Pooley et al., 2014), and funding agencies have been expanding interdisciplinary programs and opportunities. In the United States, this takes the form of, for example, the NASA IDR in Earth Science program and NSF Centers, Dear Colleague Letters, and cross-division funding opportunities such as Biocomplexity in the Environment, Integrative Graduate Education and Research Traineeship, Partnerships for International Research and Education, Dynamics of Coupled Natural and Human Systems, and a series of Science, Engineering and Education for Sustainability, and Education and Interdisciplinary Research programs. However, many of these initiatives have been short-lived, and continue to represent only a small percentage of a funding environment dominated by disciplinary research (Fox et al., 2006; Heberlein, 1988). It is too early to tell whether and how the NRC's recent call for "convergence" research (NRC, 2014) will enhance opportunities for collaborative IDR, although NSF's recognition of this form of research as one of its 10 Big Ideas (NSF, 2016) is promising (e.g., NSF Dear Colleague Letters 17-065 and 18-058, and Convergence Press Release 17-082).

3 | CASE STUDY: THE DISCCRS PROGRAM AND THE ENGAGEMENT OF EARLY TO MID-CAREER SCIENTISTS IN INTERDISCIPLINARY CLIMATE-CHANGE RESEARCH

3.1 | Introduction to the DISCCRS initiative

The NSF- and NASA-funded DISCCRS (see Mitchell & Weiler, 2011) presents a sample intervention strategy to facilitate networking and professional development of early career scientists with a self-identified interest in climate-change-focused IDR. The goal of DISCCRS was to foster interdisciplinary professional development of early career researchers and, as such, focused on scientists within 3 years of attainment of a PhD which encompassed an at least partially interdisciplinary approach set specifically in the context of climate change and its impacts. It was designed to develop an interdisciplinary (primarily physical, biological, and social sciences) network of climate-change scholars; help scholars communicate effectively with colleagues in the various disciplinary academic "rooms" and with the many audiences beyond academia; provide the team skills necessary for successful interdisciplinary collaborations; and offer professional-development skills to enable interdisciplinary scholars to navigate more successfully in a disciplinary academic world. This initiative is supported the DISCCRS website (http://disccrs.org/), which hosts career-development resources; a weekly newsletter with timely information on climate-change news and jobs; and a PhD dissertation registry, established in 2002, with a searchable database of self-submitted

abstracts of doctoral dissertations focused broadly on climate change and ranging across the physical, biological, and social sciences (further details are provided by Mitchell & Weiler, 2011).

A total of 1,247 DISCCRS dissertation registrants applied for at least one of the 8-week-long symposia held between 2003 and 2013. Applicants were reviewed and ranked by climate researchers and symposium invitees were selected based on their PhD dissertation abstract, a two-page BioSketch, two essays, and two letters of recommendation. Final selection criteria incorporated research excellence (primary) and geographic, institutional, disciplinary, and other measures to ensure a diverse cohort of participants. A total of 279 scientists attended one of the symposia (30–40 participants each); see http://disccrs.org/scholars for a list of scholars and symposium reports.

Invitees spent 6 days at a retreat-style venue interacting with, and learning from, their peers, representatives from funding agencies such as NSF and NASA, professional trainers, and carefully selected, established scientists who served as mentors. Each symposium included exposure to cutting-edge research in the physical, biological, and social sciences through brief presentations by each scholar and mid-career and senior mentors; an introduction to communication and team skills necessary in the context of IDR and communication within and beyond academia; informal networking and mentoring opportunities; and other sessions devoted to interdisciplinary professional development. Symposia scholars departed with an interdisciplinary collegial peer network, a greater understanding of other disciplinary perspectives concerned with climate change, improved team skills required for collaboration, the communication skills needed within those groups and when talking to, and writing for, other audiences, and professional skills needed to succeed in IDR.

Here, we use DISCCRS registrants and participants in DISCCRS and DISCCRS-like symposia as a sample population of early career scientists engaged in IDR to investigate the long-term impact of the DISCCRS-style model on addressing the inherent challenges to early career interdisciplinary climate-change research, and on enhancing associated success rates among young scientists. To do so, we employ publication data analysis of all scientists associated with the DISCCRS initiative (registrants–PhD graduates who registered and submitted their dissertation abstract with DISCCRS–and the subset of symposia attendees) throughout its 11-year history and participant surveys of DISCCRS PhD registrants and DISCCRS and DISCCRS-like symposia attendees.

3.2 | Study methods

3.2.1 | Survey analysis

An online survey of all DISCCRS registrants was designed to assess perceptions, challenges, and opportunities for interdisciplinary climate-change research among this select group of early-career researchers. The survey had three primary objectives: (a) identify perceptions of challenges to pursuing successful interdisciplinary climate-change research; (b) examine the role of brief interventions, such as DISCCRS symposia, in fostering interdisciplinary collegial networking and professional development and to serve as catalysts in increasing IDR broadly, and that focused on climate change specifically; and (c) crowdsource (through open-ended survey questions) ideas to generate opportunities and facilitate interdisciplinary climate-change research. In the survey, respondents selected their major disciplinary categories from a list corresponding closely to the NSF research directorates: Biological Sciences; Computer and Information Sciences; Geosciences; Engineering; Mathematics and Physical Sciences (excluding the geosciences); and Social, Behavioral, and Economic Sciences. Survey respondents were also asked to identify both their primary and secondary disciplinary expertise using a provided list of categories that spanned the directorates. In our survey we explicitly defined IDR as research "that requires collaboration (*i.e.*, research projects, proposals, publications, conference presentations and proceedings) between two or more people in distinct disciplines."

The survey targeted a total of 2,692 scientists (Table 2), including the 1,822 who registered their PhD dissertations through the web-based DISCCRS platform (this includes all who applied to and/or attended one of the eight DISCCRS symposia), plus those scientists who attended one of the eight similar DIALOG (Dissertations Initiative for the Advancement of Limnology and Oceanography), DIACES (Dissertations Initiative for the Advancement of Coastal and Estuarine Science), or NGPR (New Generation of Polar Researchers) symposia organized or co-organized by C.S. Weiler between 1993 and 2014. The survey was administered online using the Qualtrics platform (http://www.qualtrics.com/) through Whitman College in December 2014. Responses were anonymous, but were linked with information on age, gender, year of PhD completion, and PhD-granting institution, from the database of dissertation registrants, symposium applicants and symposium attendees maintained at Whitman College. The survey included 24 structured (multiple-choice, Likert-scale, and ranking) questions and four open-ended questions to elicit qualitative responses from symposium participants on their experience with IDR. The survey also presented a number of proposed interventions designed to foster support and encourage early career interdisciplinary climate-change research to respondents, and asked respondents to rank them according to perceived effectiveness. Weighted ranks were determined by calculating a score for each option represented by its weighted-average rank and alternatives were ranked based on the average score. This question also requested respondents "brainstorm" on other initiatives for the promotion of early career interdisciplinary climate-change research not presented (the "crowd-sourcing" survey component). The text of the

TABLE 2 Participation populations in bibliometric analysis and survey

Analysis group	*N*
DISCCRS-associated scientists	
DISCCRS registrants (2002 - November 2014)	1,822
DISCCRS symposia applicants	1,247
DISCCRS symposia attendees	279
Survey participation	
Total target population (DISCCRS registrants, DIALOG, DIACES, NGPR symposia applicants)	2,692
Responses requests rejected (e.g., inactive email address, full mailbox)	366
Target population reached	2,326
Total responses	616
Survey participants: DISCCRS PhD registrants only (S_{DR})	136
Survey participants: Symposia applicants, did not attend (S_{DN})	172
Survey participants: DISCCRS symposia alumni (S_{DS})	149
Survey participants: Other (DIALOG, DIACES, NPGR) symposia alumni (S_{OS})	159
Bibliometric analysis	
DISCCRS PhD registrants, did not attend a symposium (B_{DR})	799
DISCCRS symposia alumni (B_{DS})	151

complete survey is available upon request. Among the open-ended survey questions, the most significant findings are from Q1: "Please elaborate on the impact DISCCRS has had on your career." Answers from the 94 respondents (15% of the total respondent pool) to this question were entered into NVivo qualitative data analysis software (QSR International) and inductively coded into themes. This text was reviewed iteratively until no new themes emerged.

3.2.2 | Bibliometric analysis

Bibliometrics presents a developed means by which to quantify the interdisciplinarity of research, despite methodological differences and challenges cited in the literature (e.g., see review by Wagner et al., 2011). We employed a bibliometrics approach using Web of Science web services to analyze publications across 1,582 of the 1,822 researchers who registered with DISCCRS between January 2003 and November 2014. An author search was conducted using both the Science Citation Index and the Social Science Citation Index to find published original articles, designated by Thompson Reuters, which were authored by those registrants.[1]

In order to identify the impact the DISCCRS symposia may have had on attendees, only articles that were published exactly one or more years after the DISCCRS symposium attended, through to the beginning of 2014, were analyzed. While eight DISCCRS symposia have been held, only the first six were used, as insufficient time had passed between the date the analysis was conducted in 2014 and the dates of the last two symposia; in these last two cohorts, the percentage of authors with publications was too low for meaningful analysis. Of the 1,582 DISCCRS registrants at the time of the sixth symposium, our analysis used article records from 950 of them, or nearly 60%, for a total of 5,405 records. These 950 scientists were subdivided into whether they participated in a DISSCRS symposium (group B_{DS}; 151 individuals) or only registered their PhD dissertation, but did not participate in a symposium (group B_{DR}; 799 individuals) (Table 2).

We used the number of subject areas for each article record, assigned by Thomson Reuters, as a metric for interdisciplinarity. We did not use "multidisciplinary" or "interdisciplinary" Web-of-Science subject areas. We reconcile this in part because "Multidisciplinary Sciences" in the Web of Science subject areas is mostly associated with a narrower field, such as "Multidisciplinary Sciences - Chemistry" or "Multidisciplinary Sciences - Geosciences," and thus does not accurately represent multi- / interdisciplinary articles. Furthermore, it is noted that "Interdisciplinary" is a subject area only for the Social Science citation index, and hence does not appear to extend beyond the social sciences. We analyzed the number of published articles with more than one subject area, as well as the ratio of the number of articles published to the number of total subject areas, between the symposia alumni (Group B_{DS}) and those that did not attend (Group B_{DR}). Data were analyzed using Student's *t*-test ($\alpha = .1$).

3.3 | Study results

3.3.1 | Survey analysis

We received 616 fully completed surveys, yielding a response rate of 22.9% out of the original target population of 2,692 scientists; 366 of nonrespondents represent invalid email addresses and bounced e-mails (Table 2). Respondents represent

56 countries, with 374 (60%) from the United States. Twenty-two percent of the 616 respondents had only registered their dissertation with DISCCRS (Group S_{DR}), 28% had applied but not attended any of the DISCCRS symposia (not selected or opted out) (Group S_{DN}), 26% had participated in one of the eight DISCCRS symposia (Group S_{DS}), and 28% participated in either the DIALOG, DIACES, or NGPR symposia (Group S_{OS}) (Table 2). Survey respondents represent researchers from a range of fields and current occupations (Figure S1, Supporting Information), with 62% reporting that they spend at least 50% of their professional time on research. Forty-nine percent were women and 48% were under the age of 40.

Seventy-nine percent of respondents reported that their PhD dissertation work involved IDR. This is not surprising given that our survey targeted those with an expressed interest in IDR. Sixty-two percent of respondents reported that they were lead authors and 69% reported that they were coauthors on at least one peer-reviewed IDR publication. Sixty-seven percent represented scientists who completed their PhD after 2004 and the earliest PhD completion year in the data is 1984.

Survey results were examined to summarize key challenges in pursuing early career interdisciplinary climate-change research (Figure 1). Of the 588 survey participants who answered questions on challenges in IDR (28 of the 616 respondents did not answer these questions), a large majority (94%) agreed or strongly agreed that climate-change research requires an interdisciplinary approach; that IDR is more challenging for early career researchers; and that there is a need for more opportunities and IDR-relevant training at academic institutions. However, only half of respondents believe that IDR is as highly respected as research within a disciplinary field and 52% agree or strongly agree that IDR conflicts with tenure expectations. This finding highlights the persistence of perceived career challenges associated with engagement in IDR during early career stages. Exploration of the role of initiatives like DISCCRS in facilitating IDR revealed general agreement (76%) that symposium participation facilitated involvement in IDR; only 10% reported that the program had not had a long-lasting professional value to them (Figure 2). Symposia-attendee respondents were asked a series of open-ended questions about the impact of the symposium on their professional development. Three salient themes (in order of occurrence) emerged from the qualitative data, indicating that respondents felt that the DISCCRS symposia: (a) provided valuable networking opportunities; (b) changed/broadened perceptions and enhanced understanding of interdisciplinary climate-change research; and (c) enhanced the confidence and validation respondents felt about pursuing interdisciplinary climate-change research (see Box 1 for examples). These results closely follow those from postsymposia evaluations.

3.3.2 | Bibliometric analysis

The results of the publication analysis (Figure 3, Table S1) reveal that, for the overall population of DISCCRS symposia attendees, the percentage of articles published with more than one subject area was higher (i.e., more interdisciplinary articles) than for those who registered their PhD abstracts with DISCCRS, but did not attend a symposium ($p < .001$; Table 3). We found this same outcome when comparing the number of articles authored by a scientist to the number of subject areas of those publications (Figure 3b). Theoretically, it should be more difficult to show statistical significance among scholars who attended or registered in more recent years due to the smaller number of articles those scientists would have published; that is, applicants in earlier years have had more time to publish versus more recent applicants. When analyzing these metrics within

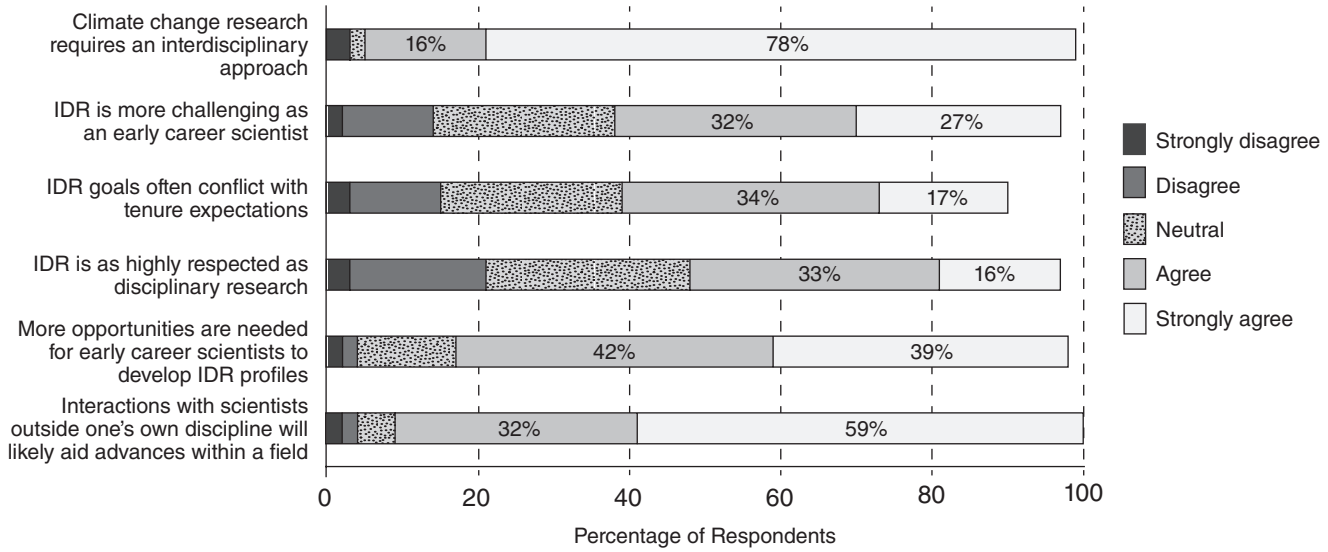

FIGURE 1 Survey responses with respect to the roles and challenges of early career interdisciplinary research. Note that the total number of responses is 588 and that percentages do not add up to 100 because N/A responses are not shown. "Neutral" responses are shown in stippled pattern and percentage values are given for dominant agree/disagree categories

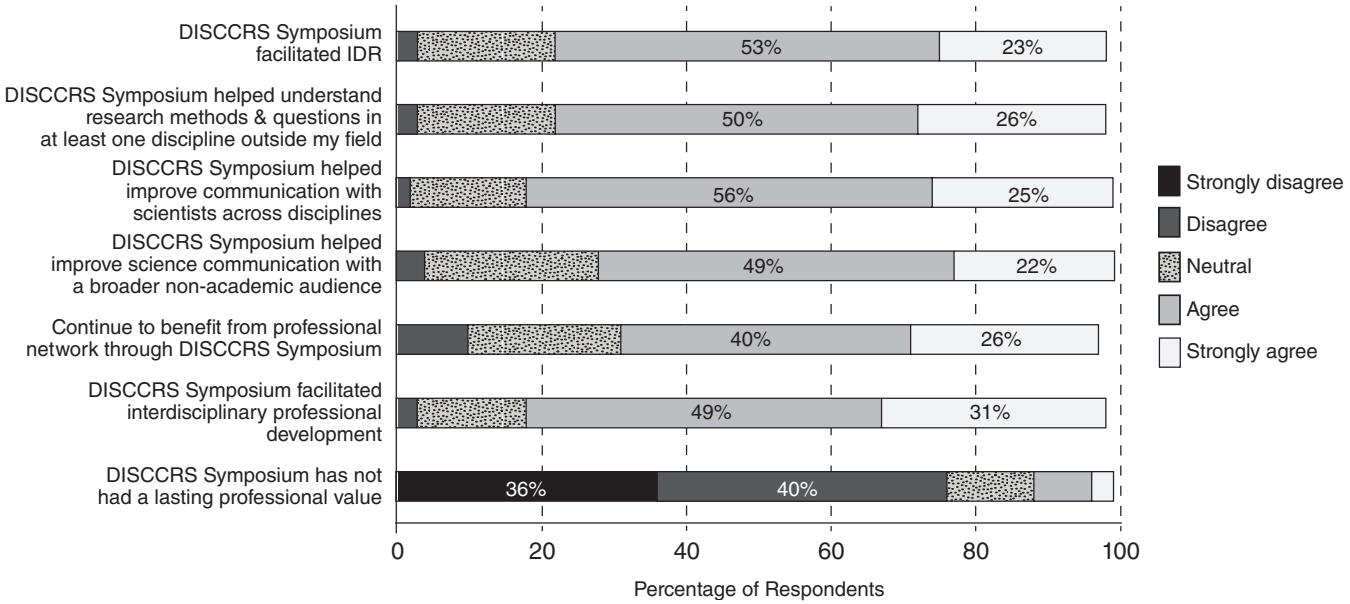

FIGURE 2 Survey responses with respect to the role of the DISCCRS or other DISSCRS-like (DIALOG, DIACES, NGPR) symposia in the promotion of early career IDR. Responses (212) are only from those who attended one of the two symposium groups: DISCCRS symposia (S_{DS}) or other, similar symposia (S_{OS}). Percentages do not add up to 100 because N/A responses are not shown. "Neutral" responses are shown in stippled pattern and percentage values are given for dominant agree/disagree categories

each year, we found significant differences in the percentage of articles published with more than one subject area between DISCCRS symposia attendees in a given year and those who registered with DISCCRS in that same period, only during the year of DISCCRS-3. Differences in the ratio of the number of articles authored by a scientist to the number of subject areas of those publications were significant for both the years 3 and 6 (Figure 3b; Table S1). This indicates that the differences in year 3, and to a lesser degree, year 6, had a strong effect on the overall significant differences observed for all symposia years combined (Table S1).

BOX 1

QUALITATIVE RESPONSES HIGHLIGHTS

Highlight No. 1: DISCCRS helped attendees appreciate the complexity of, and opportunities afforded by, interdisciplinary climate-change research. For example, "DISCCRS showed me… all of the opportunities for interesting [climate-change-focused] research projects that are taken to the next level through interdisciplinary collaboration." Respondents noted that they learned more about the challenges of IDR more broadly: the exposure to other disciplines was considered to be beneficial and, while the realization that being involved in IDR may have negative effects on professional development or the ability to raise funds, as one respondent noted, "on the other hand some of the most interesting problems are interdisciplinary"

Highlight No. 2: Connections made at DISCCRS symposia have led to coauthored papers and grant proposals, as well as establishing cohorts of support networks at conferences. Another paradigmatic response indicates that attending a DISCCRS symposium "helped with interdisciplinary interactions and has contributed to expanding my professional network. More than seven years after the [symposium] I am submitting proposals and high impact papers with a colleague I met at the [symposium]"

Highlight No. 3: Participation in a DISCCRS symposium either validated or enhanced confidence in a decision to pursue interdisciplinary climate-change research. This highlights the more nuanced sociobehavioral outcomes of interacting with other IDR-CC scholars. It seems that knowing other scholars facing the same pressures of interdisciplinary work, and understanding more directly both the challenges and benefits of such work, leveraged confidence in respondents to continue in these pursuits. Examples include: "[the DISCCRS symposium] gave me the confidence I needed to believe that being an interdisciplinary researcher was a valuable career choice"; and "*[the DISCCRS symposium] helped reaffirm for me that it is 'okay' to be an interdisciplinary researcher starting from the beginning of one's career, and gave me tools for being able to do so successfully*"

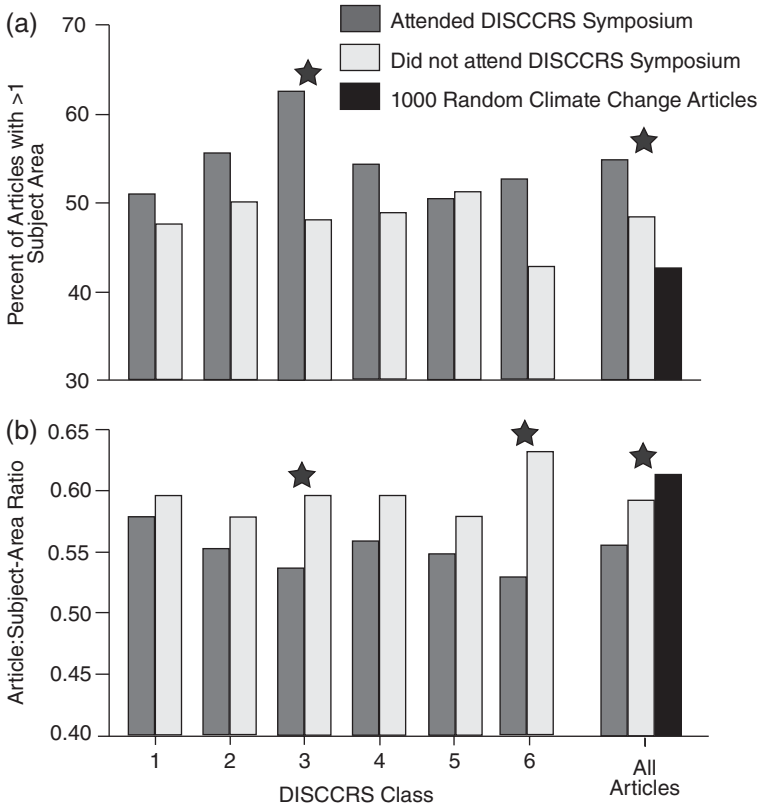

FIGURE 3 Interdisciplinary metrics of peer-reviewed publications authored by scientists who attended one of the first six DISCCRS symposia, as compared with those who registered with DISCCRS during the same time period, but did not attend that symposium. Results of analysis of 1,000 randomly selected climate-change publications are given on right. Mean data are shown by DISCCRS class (year of seminar) for the percent of articles written by a given author with >1 subject area (a) and the ratio of number of articles authored by a scientist relative to the number of subject areas of those publications (b). Therefore, a higher degree of "interdisciplinarity" is represented by a higher value (a) and a lower value in (b). Stars above bar sets indicate significant differences ($p < .001$ in [a] and $.001 < p < .062$ in [b]) between categories shown. Data, sample size, and statistical results are found in Table S1

We also compared the results from attendees across all symposia to a baseline of 1,000 randomly selected articles containing "climate change" in the title (final row, Table S1). We found that attendees published comparatively more articles with more than one subject area ($p < .001$) and fewer total articles relative to the number of subject areas spanned by those publications ($p = .001$); that is, a higher degree of "interdisciplinary" across both metrics. The percentage with more than one subject area for the randomly selected climate-change articles was even lower than the percentage for the nonattendees, possibly because all DISCCRS registrants, regardless of whether they attended the symposium, had a greater tendency toward conducting and publishing IDR.[2,3]

To further test whether these statistically significant differences in interdisciplinarity could be attributed to symposium participation itself, we performed a similar comparison between DISCCRS symposia attendees and nonattendees, but for publications less than 1 year after a given symposium. As expected, the total number of records (3,107) was substantially less than the total number of records for one or more years after the symposium (5,405), since most attendees were recent PhD graduates with only a few publications at the time. We found that, for these publications, there was no statistically significant difference between symposia attendees and nonattendee PhD registrants. This outcome suggests that the difference in more interdisciplinary articles following symposium participation may be attributed to the symposium itself. However, since symposium participation was competitive, with participants selected based on research excellence and perceived interest in interdisciplinary questions as documented in their application materials, the results may simply reflect that the organizers had successfully identified promising interdisciplinary scholars who would have shown the same professional trend even without participation in the symposium.

Our bibliometric methods follow a long history of use of multiclassification of subject areas to assess interdisciplinarity (e.g., Bordons, Morillo, & Gómez, 2004; Morillo, Bordons, & Gómez, 2003). However, we acknowledge that more nuanced and sophisticated measures exist: for example, the Rao-Stirling diversity index, which takes into account the variety in citation distributions between the journals as well as the distance between the journals in the citation network (Porter & Rafols, 2009; Rafols & Meyer, 2010). These measures provide a more robust appraisal of the connectivity between articles, journals, or subject areas: those with stronger connections and centrality to others in the network map are considered more interdisciplinary. Nonetheless, given these limitations, we maintain that our analysis provides a relatively simple and straightforward indication of interdisciplinarity and is sufficient for assessing the relative difference in interdisciplinary publications between DISCCRS registrants and attendees. For example, while a more sophisticated approach may have revealed more differences among groups, such as additional within-year differences, we found clear differences overall using our simplistic metrics among DISCCRS symposia attendees, DISCCRS registrants, and 1,000 randomly selected articles.

TABLE 3 Results of postsymposia evaluation surveys of DISCCRS symposium participants

	Symposium number								
Symposium component	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Average**
Networking with participants, informal	-	3.9	4.6	4.6	5.0	4.7	4.6	-	4.6
Team training (MBTI, facilitation)	4.5	4.4	4.0	4.8	4.7	4.7	4.4	4.7	4.4
Communication training (with public, media, etc)	4.1	4.3	-	4.6	4.7	4.8	4.4	3.9	4.4
Mentor interactions	4.6	4.4	4.5	4.7	4.7	4.6	4.5	-	4.6
NSF and NOAA program manager interactions; proposal development training	3.5	3.5	3.9	4.6	4.3	3.7	4.7	3.7	3.9
Most valuable symposium component (top answer from open-ended question)	Broader perspectives	Networking	Networking	Networking	Networking	Communication training	N/A	Networking	-
1-year postsymposium survey: Most valuable symposium component (top answer from open-ended question)	Networking	N/A	N/A	N/A	N/A	N/A	N/A	N/A	-

Written evaluations were completed on the last day of each symposium, and additional electronic survey of participants in DISCCRS-1 was completed 1 year after the symposium (response rate: 100%). Numerical ratings are given of the five most highly rated symposium components; choices (5 to 1) correspond to: *Excellent*; *Very Good*; *Good/Neutral*; *Fair*; *Poor*, respectively for symposia 1 through 5, and *Most useful*; *Very useful*; *Neutral*; *Needs some improvement or not very useful*; and *Needs major reorganization or not useful*, respectively for symposia 6–8. Outcomes of open-ended questions reflect the word best indicating the symposium component; numbers for DISCCRS-7 are not provided as a different question was asked on the evaluation form.

3.4 | Measured and perceived barriers to early career interdisciplinary climate-change research

An entire field of investigation is dedicated to explore the pursuit of effective IDR, its personal/institutional advantages, and the challenges associated with its funding, execution, and publication (e.g., Carayol & Thi, 2005; Fox et al., 2006; Frodeman, Klein, & Mitcham, 2010; Jacobs & Frickel, 2009; see also, Table 1). In addition to its potential to address expansive societal challenges, IDR may help to undermine scientific orthodoxy in established fields of exploration, or open entirely new directions for study (Barry et al., 2008; Slater & Hearn, 1996). Individual scientists participating in IDR tend to benefit through personal satisfaction provided by the ability to address issues of perceived collective importance (Blackmore & Kandiko, 2011; Bruce et al., 2004; Carayol & Thi, 2005; Jansen, von Görtz, & Heidler, 2010; Milman et al., 2017; van Rijnsoever & Hessels, 2011). Additional benefits may exist among more tangible metrics, such as enhanced likelihood of employment in academia and higher publishing rates (Millar, 2013). However, the positive personal, institutional, and scientific benefits of IDR are not always substantiated. For example, the evidence for enhanced scientific impact through employing IDR as developed using traditional measures (e.g., citation indices), at least among broadly disparate fields, is not robust and is sometimes contradictory (see Levitt & Thelwall, 2008; Yegros-Yegros, Rafols, & D'Este, 2015, and references therein). Moreover, there is a wealth of documented and perceived challenges associated with IDR endeavors; following Milman et al. (2017), these can be broadly categorized into extrinsic, systemic, or institutional-level pressures which may dissuade researchers from engaging in IDR, and intrinsic barriers imposed by IDR itself (Table 1).

In spite of advances toward supporting the interdisciplinary science from institutions and funding agencies, there remain a number of documented external challenges both to the enterprise of IDR, and faced by individual researchers. The former largely stem from an apparent penalty placed on IDR by funding agencies, journals, reviewers, and discipline-oriented scientists (Nightingale & Scott, 2007; Pooley et al., 2014; Rafols et al., 2012; Rinia et al., 2001). In part due to a tendency of IDR toward a focus on applied issues, notably in fields more generally characterized by basic scientific advances such as climate change, IDR itself continues to suffer from a perception that it remains an intellectual "fad," lacking rigor and substance; this may be compounded by the discrimination against distal specialties by disciplinarians (Öberg, 2009; Pooley et al., 2014; Rafols et al., 2012; Rhoten & Pfirman, 2007). These biases combine with the challenge of clearly identifying individual or interdisciplinary accomplishments, leading to insulation and incomplete assessment of IDR, and particularly of its interdisciplinary elements (Bergmann et al., 2005; Lau & Pasquini, 2008; Leavy, 2016). As a result, IDR may be seen as diluting a disciplinarian's core expertise, and thus may be best suited as an extracurricular, or posttenure, activity (Lattuca, 2001; Milman et al., 2017; NAS, 2004). Engagement in IDR may thus lead to difficulty in obtaining key career-advancement goals such as tenure and tenure-track academic positions, research funding, mentorship, and professional recognition (Bromham et al., 2016; Campbell, 2005; Heberlein, 1988).

These challenges were echoed by our survey population of early to mid-career scientists with self-identified interest in IDR. In particular, they indicated that their own engagement in IDR is hindered by the perception that IDR is held in lower

regard among colleagues within disciplines, and therefore, that participation in interdisciplinary climate-change research may conflict with career development and tenure goals. Many shared a concern that research which is not part of the hiring department's core discipline, or that interdisciplinary proposals and research publications themselves, may be discounted in terms of promotion consideration; this may dissuade the individual from participation. This result is in line with earlier work showing the perceived risk in pretenure engagement in IDR broadly (Mallon, 2006; Rhoten & Parker, 2004) and the explicit/implicit preference for disciplinarians shown in departmental hiring, tenure, and review procedures (Borrego & Newswander, 2008; Mallon, 2006). This is particularly relevant concern in association with project leadership and management, which are difficult to assess even in collaborative *disciplinary* projects.

Even once scientists are able to overcome (or decide to ignore) these dissuasive external pressures, they still face a secondary suite of challenges associated with conducting effective, integrated, team-based interdisciplinary studies: the "intrinsic" challenges to IDR. These partially stem from the perspective that successful IDR requires only gathering together scientists from different "rooms" to discuss discipline-spanning problems, and then to develop a common intellectual language (Fox et al., 2006; Newell et al., 2005; Salazar et al., 2012; Slater & Hearn, 1996). For example, within the field of marine science, the terms "driver" and "pressure" are often used inconsistently among natural and social scientists to refer to various physical, ecological, and anthropogenic forces affecting oceans; this may lead to misunderstanding when findings are applied to policy (Oesterwind, Rau, & Zaiko, 2016). A similar problem arises with the definition and use of "vulnerability" among interdisciplinary climate-science teams (Füssel, 2007). These communication obstacles may extend across research methods and concepts (Fox et al., 2006), to questions of spatial and temporal scales of problems, and even to the core components of the conceptual research framework (Pooley et al., 2014). Indeed, this reveals a fundamental intrinsic challenge to IDR: the competition between the desires for outcomes which advance single fields—perhaps developed in parallel within a broadly "interdisciplinary" project framework—and for those outcomes in which scientific advances are truly interconnected and derive from the combination of various disciplines (Campbell, 2005; Pooley et al., 2014; Slater & Hearn, 1996). This challenge may especially impact research developed specifically in response to a call (e.g., by a funding agency) for interdisciplinarity (Pickett, Burch Jr, & Grove, 1999). Moreover, research developed or carried out in parallel across disciplines, rather than in an integrated manner, may lead to outcomes which tend to disadvantage the social sciences, the concerns of which may motivate research questions/objectives, but whose methods and contributions are subjected to a supportive role, or worse, seen only within the context of "broader impacts" (Campbell, 2005; Fox et al., 2006; Heberlein, 1988; Pooley et al., 2014). Thus, the inclusion of economic or social sciences becomes a vehicle by which advances from the natural sciences are made societally relevant, rather than to address fundamental economic or social-science questions. Finally, even when successful, dissemination of IDR may be hindered by questions of authorship, differing expectations about the quantity and nature of publications (e.g., books vs. journal articles) across disciplines, and the need to balance both disciplinary and interdisciplinary contributions (Campbell, 2005; Mitchell & Weiler, 2011).

These barriers to engaging in successful IDR (or, at minimum, incorporating interdisciplinary components into a disciplinary profile) are common to all IDR, but may be particularly daunting in the early stages of a science career (Carayol & Thi, 2005; Heberlein, 1988; Lau & Pasquini, 2008; Livneh, Marino, & Hoeve, 2014; Marlon, Patenaude, & Barnes, 2010; Milman et al., 2017; Mitchell & Weiler, 2011; Weiler et al., 2004). For example, successful IDR requires an even higher degree of effort toward integration, but early career scientists, who are among the most likely to have exposure to (i.e., undergraduate or graduate training), and enthusiasm for, IDR, also commonly lack experience in leading (or in some cases even participating in) complex, collaborative projects, especially those stretching across disciplines. However, despite the real or perceived early career IDR disadvantages, a wide majority of our survey respondents agreed that, not only do the challenges of climate change require interdisciplinary approaches, but that scientific benefits of IDR may extend into individual disciplines. Participation in interdisciplinary climate-change research is therefore seen to improve the development of peer networks and communication, teambuilding, and interdisciplinary skills which are not yet taught in traditional "stovepipe" graduate programs, or even in some interdisciplinary programs. It may also help early career scientists build upon, and separate from, their PhD research. Based on our survey results, opportunities for publishing interdisciplinary climate-change research in high-visibility journals are not seen as a significant obstacle for DISCCRS symposia alumni, even though other studies cite this as a common problem for IDR generally (Bruce et al., 2004; Campbell, 2005; Rinia et al., 2001). This is perhaps due to the innate interdisciplinary nature of climate-change science and the prevalence of climate-change-specific journals which commonly publish IDR studies; this finding supports earlier outcomes (Milman et al., 2017; Rhoten, 2004). Finally, those surveyed here also recognize societal benefits outside of the sciences, such as enhanced communication of interdisciplinary climate-change research to the public using a trained team of scientists with interdisciplinary knowledge and understanding, as well as the societal benefits associated with climate-change research. Indeed, the ability of interdisciplinary climate-change researchers to contribute to environmental and societal sustainability appears to be a significant motivator towards IDR.

3.5 | Facilitation of interdisciplinary climate-change research among early career scientists

The outcomes of our peer survey demonstrate several critical gaps in graduate training of the current generation of early career researchers focused on an interdisciplinary approach to climate change. Furthermore, they highlight the importance of providing opportunities for students and early career researchers to develop interdisciplinary connections beyond those established in their graduate research activities, as well as the need for interdisciplinary training in communication and team skills. Although our study population is specifically (and purposefully) focused on climate change and its impacts, it is likely that these findings would translate to any field of study which requires the integration of the social, natural, and engineering sciences. Indeed, none of the challenges associated with IDR are climate-science specific (Table 1); we may presume that neither would be the solutions. Moreover, none of the challenges identified neither in our review nor in our survey would necessarily be limited to early career stages; in fact, our survey respondents largely echo the IDR challenges identified in the wealth of literature investigating IDR broadly. However, the early career period is a critical time for the development of interdisciplinary collaborations and research. This community of researchers is commonly exposed to other disciplines and receives interdisciplinary training early in their education (Bridle, Vrieling, Cardillo, Araya, & Hinojosa, 2013; Lyall & Meagher, 2012; Milman et al., 2017). Given a clear interest in IDR among young researchers, they are now being trained in interdisciplinary science faster than institutional systems can accommodate. This has led to perceived and real impediments to IDR career paths.

To this end, we present here some options for overcoming the challenges to early career IDR noted above and in Table 1, and for the promotion of interdisciplinary climate-change research as a career path, or part of a mixed disciplinary/interdisciplinary path. We argue that, because IDR requires special skills due to the collaborative nature of the process, special training and networking opportunities should become an integral part of graduate and postgraduate training.

Interdisciplinary climate-change science is not limited to academic study, and should therefore lead to additional career options for both academic and nonacademic scientists. However, within academia, interdisciplinary climate-change research has shown a clear history of development toward emerging as its own "discipline" (Weart, 2013), but has not yet emerged as such. Given this, we focus here on the specific needs of early career scientists conducting research in an academic setting dominated by disciplinary sciences. We first present the DISCCRS symposium as a potential model intervention for interdisciplinary climate-change research and then present additional strategies derived from our own perspectives and through our survey.

3.6 | DISCCRS as a model for interdisciplinary processional development

Our survey and bibliometric analysis documents that DISCCRS symposia provide an experience for early career researchers that is measurably impactful in terms of promotion of climate-change-centered IDR among early career scientists and in key metrics associated with career advancement. Among symposia-attendee respondents, large majorities felt that symposium participation facilitated their interdisciplinary professional development (80%) and involvement in climate-change-centered IDR (76%); the former also reflects team/collaboration training incorporated into the symposium, a facet commonly missing from graduate programs. Most symposium respondents further reported that the symposium enhanced their understanding of research questions and methods outside their area of expertise and enhanced science communication abilities, both across disciplines (81%) and to broader nonacademic audiences (71%). DISCCRS also had a direct positive influence in building collaborative interdisciplinary professional networks: most symposia-participant respondents reported that they have maintained professional connections with at least two (54%), or in some cases >5 (21%), DISCCRS scholars since the completion of the symposium, and 43% reported ongoing or completed research projects, coauthored papers, abstracts, and proposals, coorganized conferences and special sessions, and cross-recruitment of graduate students and postdocs with other DISCCRS scholars. This was also the most common benefit of DISSCRS symposium participation identified in responses to qualitative questions (see Box 1).

These findings support perceptions reported by DISCCRS symposia attendees on written evaluations completed onsite on the last day of each symposium, as well as those from a postsymposium evaluation electronically sent to all participants of the first symposium 12 months after the symposium ended (Table 3; see also Mitchell & Weiler, 2011 and Weiler et al., 2004). Attendees felt that the most useful components of symposia were the informal networking opportunities with their peers, interactions with mentors, training in communication, and development of interdisciplinary team skills. In spite of expressed concerns related to jobs, proposal writing, and funding, interactions with federal agency program managers and proposal development were the lowest-ranked symposium element. This is perhaps because attendees perceived that these opportunities were available elsewhere, although this DISCCRS component still received a ranking just below very good/very useful (Table 3). In a series of open-ended evaluation questions, symposium participants frequently commented that communication and (especially) team skills were rarely part of their graduate training, and that the most valuable components of the symposia

were (in order of occurrence) networking (with mentors and among co-participants), broadened perspectives, team training, agency representative interactions, communication training, and mentor interactions.

Perhaps the most intriguing outcome from our survey was the large number of respondents who noted participation in a DISCCRS symposium was validating or confidence-building for their decision to pursue climate-change-centered IDR. This finding highlights the more nuanced sociobehavioral outcomes of interacting with other interdisciplinary scholars, and also points to the pressures experienced by early career scientists when choosing which research problems to pursue. While this perception of enhanced confidence may or may not lead to a more (successful) interdisciplinary career over the long term, our bibliometric analyses (Figure 3; Table S1) demonstrate that DISCCRS symposia alumni authored/coauthored more multi-/interdisciplinary publications than those of early career scientists who expressed interest in interdisciplinary climate-change research (registered PhD dissertations) but did not participate in a symposium. Thus, across multiple perceived and measurable metrics, symposium participation appears to have led to a net shift toward interdisciplinarity, in spite of the recognized challenges.

Together, our survey (both qualitative and quantitative components) and bibliometric outcomes suggest a measurable positive impact of DISCCRS symposium participation on the opportunities for, and ability to successfully engage in, interdisciplinary climate-change research. We do, however, recognize some limits to the generalizability of our study. Foremost, our study sample of DISCCRS dissertation registrants, DISCCRS symposia applicants, and DISCCRS and other symposia alumni is inherently biased toward scientists with a self-selected interest in interdisciplinary climate-change research (this is in part accounted for through comparison of bibliometric results against 1,000 randomly selected climate-change publications). Moreover, participants in a DISCCRS symposium were chosen through both self-identification (a scientist had to be motivated to apply for symposium participation) and a competitive process that sought to select participants based on research excellence and proven record of IDR. Thus, comparisons between symposium attendees and the group of unselected symposium applicants and dissertation registrants may reflect that the organizers were successful in identifying promising interdisciplinary scholars. Identifying an appropriate comparison group is an ongoing challenge for studies of this nature (e.g., those investigating the impacts of participation in Research Experience for Undergraduates [REU] programs).

Additionally, our survey analysis reflects perspectives of scientists with a self-reported interest in interdisciplinary climate-change research. Though our sample was evenly split between researchers that were exposed to DISCCRS-style symposia and those that were not, we note that about 80% of our survey respondents were primarily experts in the biological sciences and geosciences (Figure S1); this limits our ability to generalize across the broad range of disciplines that address climate science. Finally, our bibliometric analysis suffers from the use of subject areas as an accurate proxy for interdisciplinarity: some subject areas—and we would argue the field of climate science in general—are inherently interdisciplinary. However, the results indicate a statistically significant difference between the DISCCRS symposia alumni and the nonattendees, or those selected randomly across all climate-change publications; this reinforces the indication that attending a DISCCRS symposium did have an overall impact on the research habits of these authors, but we cannot confirm a causal link. This impact was likewise reflected in the perceptions of those who attended a DISCCRS symposium, as shown by generally more positive feelings toward engagement in, and impact of, IDR, as well as higher self-perceived IDR productivity (participation in interdisciplinary proposals, projects, and publications) among symposia alumni.

Nonetheless, even though climate-change science provides a tangible and societally relevant topic around which scientists from various disciplines can congregate, application of this symposium model to bring together early career scientists from across disciplines to discuss the opportunities, benefits, and potential pitfalls of incorporating interdisciplinarity into their careers may well benefit any number of interdisciplinary challenges.

3.7 | Mechanisms for the promotion of early career interdisciplinary climate-change research

DISCCRS-like symposia provide a mechanism to promote and foster interdisciplinary networking, collaboration, and training. Similar workshops, including "encounters" and "masterclasses" focused specifically on graduate students, postdoctoral researchers, and early career faculty have also been employed to at least start to present solutions to overcoming the intrinsic and extrinsic barriers to successful IDR (Bridle et al., 2013; Lyall & Meagher, 2012). However, such workshops require coordination and at the national/international level, are costly, and are limited to a small subgroup of early career scientists. Thus, in addition to development of the next generation of (inter)national DISCCRS-like symposia, many of the symposium components could be incorporated within academic institutions, for example, through cross-department activities, or at a regional, multiinstitutional scale, to reduce costs and increase availability to a wider audience. Alternatively, interdisciplinary, cross-departmental centers, graduate programs, and postdoctoral research opportunities and fellowships, such as those (nonclimate-change specific) programs described by Biancani, Dahlander, McFarland, and Smith (2018), Brint, Turk-Bicakci, Proctor, and Murphy (2009), Evans and Randalls (2008), Gardner (2011), and Graybill et al. (2006), may serve to promote active interdisciplinary, climate-change-centered training across widely separated fields at early career stages. Even earlier, undergraduate

students would benefit from taking courses outside of their disciplinary specialty (or those specifically targeted to interdisciplinarity, for example, Kurland et al., 2010), exposure to interdisciplinary climate-change-related education projects (e.g., McCright et al., 2013), and encouragement to pursue minors in different areas depending on their interests. Such approaches could help shape the perspectives of future academics, enhancing comfort and fluency with the concepts, approaches, and terminology of different disciplines at an early stage, and thereby countering several extrinsic and intrinsic barriers to later engagement in IDR, such as those associated with perception, assessment, conceptual framework, disciplinary balance, and internal communication.

Our survey requested that respondents rank seven proposed mechanisms designed to support early career interdisciplinary climate-change research (Figure 4). While none of the seven options presented could be achieved without financial burden, the top two choices (>50% of top rankings) require the highest degree of institutional-level investment in climate-change-focused interdisciplinarity, specifically through funding of IDR/development seed grants for principal investigator (PI)s or graduate/postdoctoral fellowships. Doing so may improve the stature and funding of IDR and its practitioners, thereby reducing extrinsic challenges associated with funding and career placement and advancement. The majority of "other" (crowd-sourced) suggestions not reflected in the seven broad initiatives in Figure 4 also highlighted both external and institutional funding sources, and ultimately a cultural change in academia through a revision of evaluation criteria as key factors for successful IDR initiatives. Opportunities for sustained, regular interactions across disciplines, but within single institutions, are at the core of creating an environment that is conducive for IDR: two of the top three initiatives identified were of this type (interdisciplinary climate-change-research seed funding; interdisciplinary student, postdoctoral and/or junior faculty networks). Together, these would help provide funding (an extrinsic systemic barrier) to improve interdisciplinary fluency and fulfill some of the educational and training needs (extrinsic systemic barriers) through hands-on engagement in IDR, thereby providing experience to counter some of the intrinsic barriers to IDR. Institution-level DISCCRS-like symposia (rank #4) were seen as superior to topical sessions at scientific conferences or institution-scale single day, interdisciplinary conferences or symposia, likely reflecting the benefits of extended, focused retreats to build peer networks, engage in interdisciplinary training, and foster development of interdisciplinary communication and collaboration skills. The value of communication of research ideas and methods across disciplines is clearly positive to participants of such symposia but the broader, intangible value of changing the culture of research and education in the university system needs further emphasis.

Training in communication and team skills were particularly valued by the interdisciplinary DISCCRS symposium participants (Table 3), and such training could be offered through classes and/or participation in community activities such as Toastmasters and "little theatres." Many institutions already offer training in improvisational acting (a major part of the *Alan Alda Communication Training* for scientists) and in psychology/teamwork. Such training should be made more available, and could be accomplished at relatively low cost using existing faculty and institutional mechanisms.

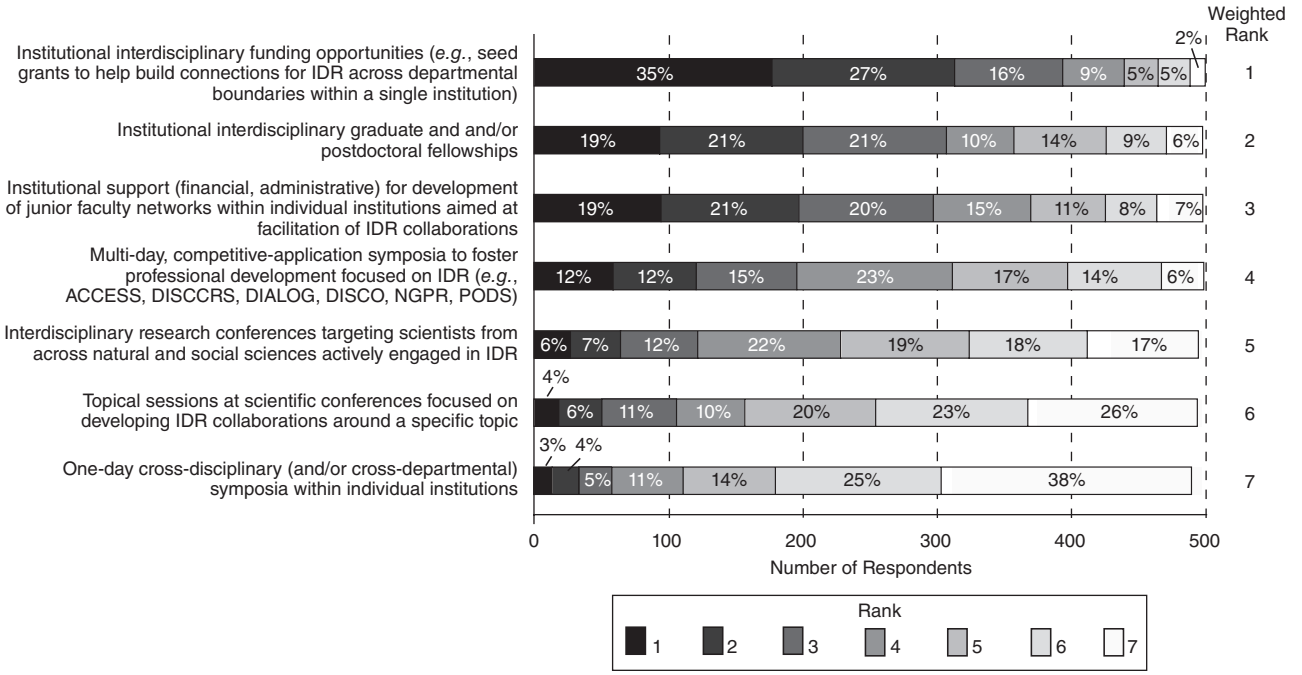

FIGURE 4 Survey responses ranking initiatives to promote early career interdisciplinary research, based on 499 survey participants who responded to this question. Total responses to each initiative are not the same because N/A responses are not shown. Percentages are of total number of respondents for a given initiative, and are provided for all categories with >15% of responses

A final proposed mechanism for the promotion of early career interdisciplinary climate-change research (or IDR generally) is the broad use of targeted mechanisms for identifying and recognizing interdisciplinary contributions by hiring, tenure, and promotion committees. For example, bibliometric-based science mapping—spatial representations of the relationships between disciplines, journals, publications, keywords, or authors to display dynamic aspects of research fields or topics (Small, 1999)—may allow assessment teams to situate the breadth of expertise of researchers (at least for those with an expressed IDR profile) (e.g., Cobo, López-Herrera, Herrera-Viedma, & Herrera, 2011; Klavans & Boyack, 2007; Leydesdorff, Carley, & Rafols, 2013; Porter & Rafols, 2009; Rafols et al., 2012; Wagner et al., 2011). While these require database development and may not always provide a quantifiable metric of an individual scientist's interdisciplinarity, depending on disciplinary classification schemes and specific algorithms (Adams, Loach, & Szomszor, 2016), such techniques have been found to provide a means to visualize disciplinary connections (e.g., Leydesdorff & Rafols, 2009). Semi-quantitative mapping of this nature, combined with subjective assessments of intersubjective integration and agreement, IDR project management/leadership, approval by peers and the broader community, and—particularly in the field of climate science—impact on broader society, may better allow for recognition of a researcher's contributions across disciplines, thereby hopefully mitigating some of the apparent extrinsic IDR assessment penalties.

4 | CONCLUSION

There is broad recognition of the extrinsic and intrinsic challenges to successful IDR, including those associated with acknowledgment of scientific contributions within an interdisciplinary framework and the explicit conceptual, communication, and organizational challenges of conducting meaningful, integrated IDR. Nonetheless, a new paradigm of collaboration is required for IDR, such as that associated with (a) the study of the causes of, and the natural, social, and economic system responses to, climate change; (b) the development of best practices for adapting and mitigating the resulting challenges; and (c) the outreach to policy makers and the broader public to ensure that decisions are made based on the most comprehensive science available. None are likely better suited to this task than those early in their scientific careers, and the next generation of scientists whom they are today teaching, advising, and mentoring. Indeed, given their early career status, these scientists are expected to be among those most exposed to, and well-trained in, interdisciplinarity, but also those for whom deep engagement in IDR carries the greatest career risk. This group represents part of the upcoming cohort of researchers, educators, and administrators across academia, government, and the private and nonprofit sectors who are actively working across the natural and social sciences to address pressing scientific and societal issues such as those associated with climate change. Our survey of early to mid-career scientists demonstrates the perceived needs for: (a) expanded training (notably in communication and team skills) and networking opportunities, such as those provided by the DISCCRS symposia and (b) encouragement from senior colleagues and institutions, in order for interdisciplinary climate-change research to become an integrated, if not dominant, component of an early career scientist's research profile. This will serve to enhance connectively across the ever-growing and ever-more-complex field of climate science, and raise the profile of IDR generally as these scientists develop into leaders within and across their disciplines.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

ENDNOTES

[1]As web services searches may only contain initials for the first and middle names, searches often returned articles that were written by a variety of authors. For example, searches on common last names (e.g., Zhang) often returned thousands of articles. To help ensure that articles were correctly attributed to DISCCRS registrants, authors with common last names were

excluded from the analysis, and only article records that contained the authors' first and last names were used. Furthermore, some authors were not found in the web services search. As a result, not all articles were retrieved for all DISCCRS registrants. However, since our goal was to analyze article attributes on a per-article basis, comparing individuals who did (Group B_{DS}) and did not (Group B_{DR}) attend a symposium (Table 3), retrieving only a portion of the articles (assuming those retrieved were representative of the population) was deemed acceptable.

[2]We also analyzed a similar number of randomly selected climate-change articles where the distribution of published year across all articles was equal to the distribution of published year from the total DISCCRS attended population to ensure that the published year did not have an effect on the results. The alternate analysis showed a very similar result: DISCCRS attendees were more multi-/inter-disciplinary ($p < .001$).

[3]We also found the ratio of articles to subject areas was lower (i.e., more multi-/inter-disciplinary) among symposium attendees for all symposium cohorts combined ($p < .005$); within-years, this difference was significant for two of the six cohorts ($p < .1$). Comparing the DISCCRS attendees to the 1,000 randomly selected climate-change article baseline, the ratio of articles to subject areas was lower and thus more multi-/inter-disciplinary for the attendees ($p < .001$).

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FURTHER READING

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