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Author(s): Stephanie E. Hampton and John N. Parker

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STEPHANIE E. HAMPTON AND JOHN N. PARKER

Scientific synthesis has transformed ecological research and presents opportunities for advancements across the sciences; to date, however, little is known about the antecedents of success in synthesis. Building on findings from 10 years of detailed research on social interactions in synthesis groups at the National Center for Ecological Analysis and Synthesis, we demonstrated with large-scale quantitative analyses that face-to-face interaction has been vital to success in synthesis groups, boosting the production of peer-reviewed publications. But it has been about more than just meeting; the importance of resident scientists at synthesis centers was also evident, in that including synthesis-center residents in geographically distributed working groups further increased productivity. Moreover, multi-institutional collaboration, normally detrimental to productivity, was positively associated with productivity in this stimulating environment. Finally, participation in synthesis groups significantly increased scientists' collaborative propensity and visibility, positively affecting scientific careers and potentially increasing the capacity of the scientific community to leverage synthesis for enhanced scientific understanding.

Keywords: synthetic science, sociology of collaboration, interdisciplinary science, scientific metrics, research productivity and impact

Synthesis is increasingly recognized as an essential component of the scientific endeavor (Carpenter et al. 2009a). *Scientific synthesis* refers to the integration of diverse research in order to increase the generality and applicability of the results of that scientific research (Hackett et al. 2008, Carpenter et al. 2009a, Hackett and Parker 2011). At its core, synthesis is about blending disparate information and knowledge in ways that yield novel insights or explanations (Pickett et al. 2007). Synthesis occurs both within and across disciplines and professional sectors and is therefore not captured entirely by the term *interdisciplinary research.*

Synthesis plays a broad role in enhancing scientific understanding. First, synthesis provides a crucial counterweight to hyperspecialization in science. Although greater specialization may lead to an increasingly sophisticated understanding of specific phenomena, overspecialization can lead to findings of little direct social relevance and can hinder research falling outside or between well-specified domains (Kostoff 2002). Synthesis helps ameliorate these problems (Wilson 1998, Carpenter et al. 2009a). Second, many disciplines now grapple with a situation that would have seemed ludicrous even two decades ago: too much data (Carlson 2006, Bell et al. 2009). Synthesis provides a method of coping with and capitalizing on this data deluge, which allows analyses at previously unimaginable scales and facilitates new discoveries. Third, the diversity of expertise, skills, and data inherent in a synthesis endeavor enhances the capacity for transformative research and serendipitous discoveries (Hackett et al. 2008). Fourth, synthesis allows for the conceptualization of complex social and environmental problems beyond the scope of any one profession, discipline, data set, or research approach (AC-ERE 2003, Carpenter et al. 2009a). Finally, synthesis is significant in terms of societal investment. Since 2006, the US National Science Foundation (NSF) has awarded more than $43 million to synthesis-center initiatives and recently announced an additional $27.5 million commitment to its fourth synthesis center. International efforts at promoting synthesis are also on the rise, with organizations such as the Stockholm Resilience Center (Sweden), the Institute Para Limes (the Netherlands), and the Australian Center for Ecological Analysis and Synthesis rapidly developing new synthetic programs over the past several years.

Still, virtually nothing is known about the factors related to success in synthesis, how participation in synthetic research shapes scientific careers, and what this may teach us about how to design synthesis initiatives. In this article, we consider these issues. First, we briefly review evidence for the effectiveness of the synthesis approach and then more fully examine the anatomy of successful synthesis projects, using 15 years of data on projects from an ecological synthesis center. This article addresses this general question: What factors of group composition and process predict scientific productivity and visibility in synthesis groups and does the experience alter participants' careers in measurable ways? We capitalize on the availability of data about peer-reviewed publications as indicators of success, but also recognize that success can take many forms in the scientific endeavor.

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Synthesis at the National Center for Ecological Analysis and Synthesis

The NSF initiated a revolution in ecological research by establishing the National Center for Ecological Analysis and Synthesis (NCEAS) in 1995 (Hackett et al. 2008). NCEAS was created in response to broad acknowledgement within the ecological research community that an inability to meaningfully synthesize accumulating ecological information was seriously hampering scientific understanding and environmental decisionmaking (Brown and Carpenter 1993). Managing this challenge necessitated a radically new approach to conducting ecological research. First, no new data were to be collected; rather, the emphasis would be on the creation of new knowledge by synthesizing existing data. Second, the center would be a resource for the scientific community at large and would not be focused on a specific line of research. Third, the center's primary function would be providing the time, resources, and creative environment in which visitors could completely immerse themselves in collaborative synthesis.

> *We are drowning in information while starving for wisdom. The world henceforth will be run by synthesizers, people able to put together the right information at the right time, think critically about it, and make important choices wisely.*
>
> —Edward O. Wilson, *Consilience: The Unity of Knowledge*

By 2005, the center had risen into the top 1% of the 38,000 institutions worldwide publishing in ecology and environmental sciences in terms of scientific impact (Hackett et al. 2008). The average impact factor (IF) for NCEAS publications is substantially higher than the average for top ecology journals (IF = 8.2, compared with an average of 6.75 for 2008's five most highly ranked ecology journals), and two of the three most influential publications on the ecological response to climate change in 2010 were NCEAS products (ScienceWatch 2009). On the basis of these successes, at least 18 research centers worldwide have embraced the NCEAS model of facilitating synthetic research.

The most widely emulated aspect of NCEAS is its characteristic mode of collaboration: working groups that are convened specifically to synthesize existing data. For example, this approach has been incorporated into the NSF-funded National Evolutionary Synthesis Center (NESCent) and the National Institute for Mathematical and Biological Synthesis (NIMBioS), as well as the US Geological Survey's Powell Center for Ecological Analysis and Synthesis. The groups typically consist of 8–15 collaborators, who convene face to face at NCEAS in Santa Barbara, California, to engage in deep analysis and synthesis of theory, methods, and data. The groups usually meet for about a week, often for 10–12 hours each day, several times each year, over two or three years. In addition to these face-to-face meetings, the working group members continue their research at their home institutions until the next group meeting.

Almost all of the working groups involve several members of the resident NCEAS community. The resident community is numerically dominated by postdoctoral researchers, based at NCEAS for two or three years at a time, who each participate in multiple working groups. NESCent and NIMBioS also support resident postdoctoral scientists who interact with visitors in the working groups.

Sociological research on NCEAS working groups (including ethnographic observations, in-depth interviews, attitudinal surveys, and social-network analysis) have taught us much about microsocial interactions in this collaborative environment (Rhoten 2003, Hackett et al. 2008). The long hours of intensely focused face-to-face collaboration, in a location free from outside distractions, facilitate effective and rapid communication and problem solving and significantly increase the velocity at which ideas are generated. As in other settings (Collins R 1998, Farrell 2001), these conditions also yield high degrees of instrumental trust (trust associated with judgment of risk), limit conflict (Shrum et al. 2001), and facilitate creativity, which allow the collaborators to share ideas and data freely. The diversity of scientific expertise present in these groups, a focused yet flexible research agenda, and concentrated interactions with minimal distractions also increase the potential for serendipitous research and discovery. Furthermore, the majority of these collaborators maintain that their experiences in these working groups will increase their future collaborative propensity (74%) and willingness to share data (77%) (Hackett et al. 2008).

NCEAS has now collected longitudinal data on more than 200 synthesis working groups, and the opportunity to complement previous qualitative microanalyses with large-scale quantitative analyses now presents itself. Such analyses are important for both the basic insights that they can reveal about this distinctive form of research and as a basis for future synthesis efforts. Both of us (the present authors) are supported by the research center that yields these data; in taking this quantitative approach, our goal is to present the results in a manner that promotes objective assessment.

NCEAS project selection. Working group proposals generally have been solicited twice annually since the inception of NCEAS. The NCEAS science advisory board, a group of experts in ecology and its allied fields, has assessed the scientific merit of NCEAS group proposals, while also considering group composition and size, and has attempted to maximize the appropriate disciplinary, institutional, and geographic representation. After being selected, NCEAS directors (including present author SEH) have taken a laissez-faire management approach, which allows working group leaders the autonomy and flexibility to organize group activities according to their needs.

Working group composition and activity. Data on group size, some participant demographics, and the timing of meetings are readily available in the NCEAS administrative database. Participants are asked to report the professional societies to which they belong, although these data are sparse in the early entries in the NCEAS database. The societies can be assigned to a variety of disciplines, such that disciplinary diversity within a working group can also be analyzed. For this analysis, 131 groups conforming to the standard NCEAS selection process were included.

Publications. We analyzed only peer-reviewed journal publications (*www.nceas.ucsb.edu/products*), because metrics involving peer-reviewed publications are widely used in the assessment of scientific endeavors. Citation information was downloaded from the Science Citation Index (SCI; *http://thomsonreuters.com/products_services/science/science_products/a-z/science_citation_index*; Thomson Reuters, New York). The IF recorded for each publication reflects the IF of the journal in the year in which it was published. To allow us to more readily consider citation rates over time, we added up the citations each paper received within the first three years of its publication and analyzed the average three-year citation totals for the publications produced by each project. The analysis of the three-year citation totals excluded 23 working groups for which no SCI-indexed publications were produced, either because no journal publication data were yet available or because the journals were not indexed. On 31 January 2009, we took a "snapshot" of the database, such that we are working only with data reported before this date.

Analyses of working group trends, productivity, and impact

We used multiple regression analyses to explore potential predictors of the productivity and impact of publications reported as NCEAS products. The factors in our database that are likely to affect group productivity and publication impact can be roughly classified as aspects of the time the group spends together, the group's size, and the group's composition (table 1).

Time is an elemental facet of scientific productivity (Kim 2005); we expected that groups involved in longer, more frequent meetings with shorter interludes between them would be more successful. In these respects, five different temporal characteristics might potentially affect working group productivity and impact. We expected that the groups meeting more often, meeting for longer durations, and meeting for a greater total number of days would be more productive, because they have had more time to conduct research;

Table 1. Variables selected to predict aspects of productivity and impact in forward–backward model selection.

Variable category	Variable	Number of publications	Average number of citations after three years
Fit	r^2	.33	.11
Time	Start date	–	
	Total number of meetings	+	+
	Average meeting duration	0	
	Average time between meetings		
	Total days together		
Group size	Total number of participants	+	
	Average meeting size		
	Total number of meetings × average meeting size		
	Total number of meetings × total number of participants		
	Average meeting duration × average meeting size		
	Average meeting duration × total number of participants		
Group composition	Total number of residents	+	
	Institutions/participants	+	
	Average percentage total participants at meetings		+
	Percentage female		
	Percentage non-US		
	Percentage leaders among participants		0
	Total number of meetings × percentage total participants at meetings		
	Total number of meetings × total number of residents		
	Average meeting size × total number of residents		
	Total number of participants × total number of residents		
	Total number of meetings × total number of institutions		
	Average meeting duration × total number of institutions		
	Total days together × total number of institutions		

Note: The response variables were log transformed to account for potential nonlinearities and to improve adherence to normality assumptions. We did not exclude outliers, after verifying that the recorded information was accurate (Neter et al. 1996). The minus sign (–) indicates a significant negative effect, and the plus (+) indicates significant positive effects at $\alpha = .05$, whereas 0 indicates that the effect was retained during model selection but was not significant in the final model.

publish scientific papers; establish roles; and build the commitment, cohesion, and coherence of vision required for collaborative success (Collins R 1998, Hackett et al. 2008). We further expected that the working groups supported earlier in the history of NCEAS would be more productive, because they have had more time to bring their work to fruition. We expected that longer periods between working group meetings would result in lower rates of success, because those groups' cohesion and focus would decay, which would require the devotion of greater time at the beginning of each meeting to reintegrate the group as a social unit and to return to the aims for which it was organized. We further anticipated that complex interactions might occur among these variables (table 1); for example, the negative effects of increasing time lapses between meetings could be lessened if the meetings were longer in duration.

Group size is a second fundamental aspect of scientific productivity; evidence from a wide variety of studies suggests that productivity increases with the addition of collaborators but that above a certain group size, further additions result in diminishing returns, no effect, or even a decrease in productivity (Von Tunzelmann et al. 2003). Given these findings, there exists the potential for two different aspects of group size to affect working group productivity. Foremost, we hypothesized that the total number of unique collaborators involved in a working group would affect that group's productivity. Note, however, that not all collaborators associated with a particular NCEAS working group attend each group meeting. Rather than the total number of collaborators, it may therefore be that the average number of collaborators within each working group meeting is a better predictor of productivity. We expected that a curvilinear relationship would exist for the average size of the group meetings as the meeting size becomes unwieldy.

Finally, it is increasingly recognized that a diverse group composition is necessary to produce transformative research of relevance to major social and environmental problems (AC-ERE 2009) but that such diversity can also dampen productivity (Corley et al. 2006, Cummings and Kiesler 2005, 2007, Parker 2010). Working groups involving greater numbers of disciplines and institutions should therefore be significantly less productive. Publication characteristics can also vary with group members' gender (Long 1992, Leahey 2007) and country of origin (Fava and Ottolini 2004), so these variables were included to control for their potential influence. We further expected leadership and experience conducting synthetic research, such as the experience provided by NCEAS residents, to shape productivity and impact. Groups with a greater number of leaders (which was measured as the number of principal investigators on the original proposal) and that included greater numbers of NCEAS residents should be more productive; these individuals should demonstrate greater project commitment, provide more scientific experience and expertise, and enhance the ability of the group to maintain focus (Babu and Singh 1998, Cummings and Kiesler 2008).

Trends in working group activity and productivity. Many aspects of the working groups have remained highly variable over time, without a discernible trend (table 2). The meetings may have become, on average, a little shorter, but they did not demonstrate a significant trend. In the first few years, several very small groups had relatively long meetings (e.g., several weeks), and this mode became less popular. The average interval between meetings has been similar over time. The overall number of participants, totaled across all meetings of the working group, has remained steady over time. However, the average size of each meeting and the consistency of the group composition have increased significantly over time. Originally, it seems to have been more common for working groups to organize subgroup meetings, with less overlap of participants from one meeting to the next. The proportions of women and non-US participants have increased. As is the case across ecology and the environmental sciences, the number of authors on NCEAS papers has markedly increased, from an average of four authors in 1996 to an average of nine authors 10 years later. This acceleration of collaboration (0.5 author per year) within NCEAS working groups is more than sixfold the rate of increase (0.08 author per year) seen during the same time period in a random subsample of publications from five randomly selected journals in which NCEAS authors regularly publish.

An enduring observation regarding scientific productivity is that it tends to be unequally distributed (figure 1). The conformation of scientific productivity to power-law distributions is one of the most well-established findings in sociological studies of science (Lotka 1926, Price 1963, Patra and Mishra 2006). In general, relatively few researchers and groups tend to be responsible for the vast majority of publications. Such is also the case at NCEAS, where about 30% of the working groups produce roughly 70% of the working group journal articles (figure 1). This result raises the question of what determines working group productivity and impact.

Influences on working group productivity. Our multiple regression analysis revealed the importance of group process, composition, and institutional diversity for scientific productivity in synthesis groups (figure 2). The strongest predictor of group productivity was the number of working group meetings, subsuming all other temporal effects (i.e., the average duration of working group meetings, the total days together, the average time between working group events) except total project length (the number of days between the project's start and its end). Complementing the findings from structured observations, interviews, and attitudinal surveys (Rhoten 2003, Hackett et al. 2008), this result suggests that the benefits supported by these face-to-face meetings are not simply a matter of the time allotted to research but also of the sociological aspects of meetings that foster productivity.

The second-strongest predictor of productivity was the total number of collaborators. Contrary to past research, we

Table 2. Trends in working group composition and activity from 1995 to 2009 were examined using simple linear regression, after confirming that temporal autocorrelation was not detectable (by Durbin–Watson test, p > .05) in the individual variables.

Variables tracked over time	r^2	p	Mean	Standard deviation	Range
Number of meetings	.007	.343	3.7	2.0	1.0–13.0
Meeting duration in days	.016	.140	5.8	4.5	2.0–42.0
Days between meetings	.003	.554	255.6	125.8	48.5–812.0
Total number of participants	.001	.666	19.9	10.4	2.0–69.0
Average meeting size[a]	.071	.002	12.8	5.1	2.0–25.3
Average percentage of total participants at meetings[a]	.037	.026	71.2	20.4	18.4–100.0
Number of residents participating	.014	.167	1.0	1.3	0.0–6.0
Percentage of female participants[a]	.039	.021	25.6	15.6	0.0–100.0
Number of leaders on original proposal[a]	.059	.004	2.1	1.1	1.0–6.0
Percentage leaders in group	.013	.191	22.1	18.2	2.5–100.0
Number of non-US participants[a]	.061	.004	2.5	2.1	0.0–9.7
Number of distinct institutions	.003	.505	15.0	7.6	2.0–51.0
Number of distinct societies	.019	.124	13.6	6.7	1.0–36.0
Number of distinct disciplines	.011	.245	5.4	2.4	1.0–13.0
Number of authors per article[a]	.095	.001	6.1	4.9	1.0–37.4

[a]Variables that have significantly increased over time. None of the present variables had significant negative trends.

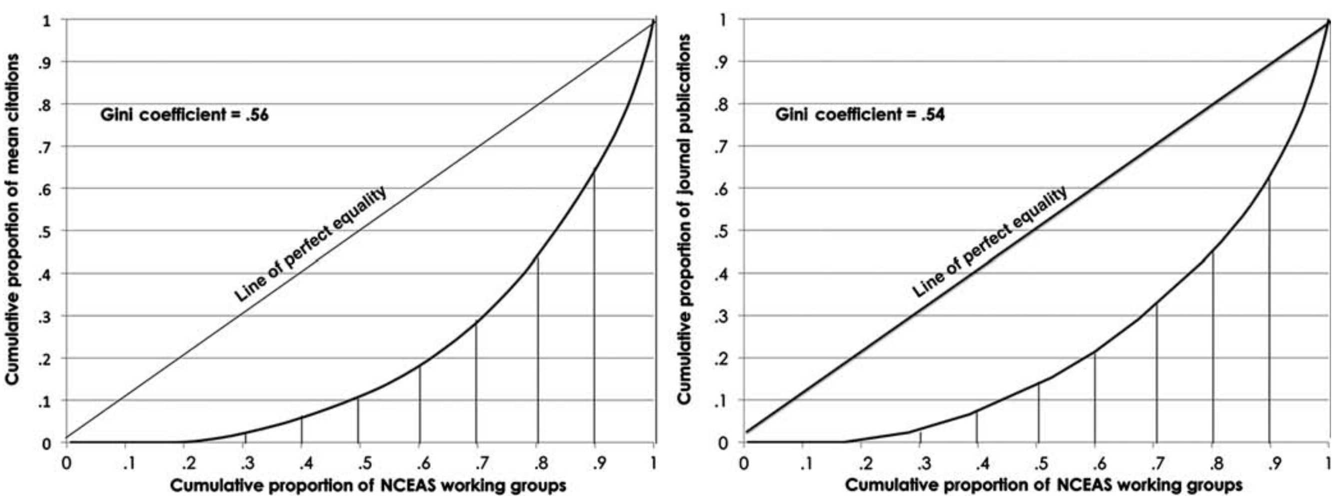

Figure 1. Lorenz curves and Gini coefficients (Allison and Stewart 1974) assess the degree of inequity in scientific productivity and citedness among NCEAS working groups.

found limited evidence of diminishing returns with increasing group size.

To explore the potential for productivity to plateau at larger group sizes (Von Tunzelmann et al. 2003), we compared a polynomial fit with a linear fit of the average meeting size that predicted the total and per capita number of publications. The polynomial fit (r^2 = .05, p =.07) did not appear to be better than the linear fit (r^2 = .04, p = .04) for predicting the increase in total publications with increases in working group size. However, although the total number of publications did increase with increasing group size, the per capita contributions declined with increasing group size (linear fit, r^2 = .11, p < .01; polynomial fit, r^2 = .12, p < .01). The surprisingly weak evidence for diminishing returns with increased group size may relate to several factors. First, the range of group sizes that we have examined here has been restricted by the physical space and by the policies of NCEAS, which limit meeting sizes to about 30 people. Second, by design, there should be limited redundancy of knowledge and skills in synthesis groups (e.g., table 2); each person would therefore be more likely to offer unique contributions. Third, the ease and speed of communication facilitated by these highly focused meetings may allow greater numbers of participants to make meaningful contributions.

The working groups that included greater numbers of center residents (i.e., postdoctoral fellows, sabbatical

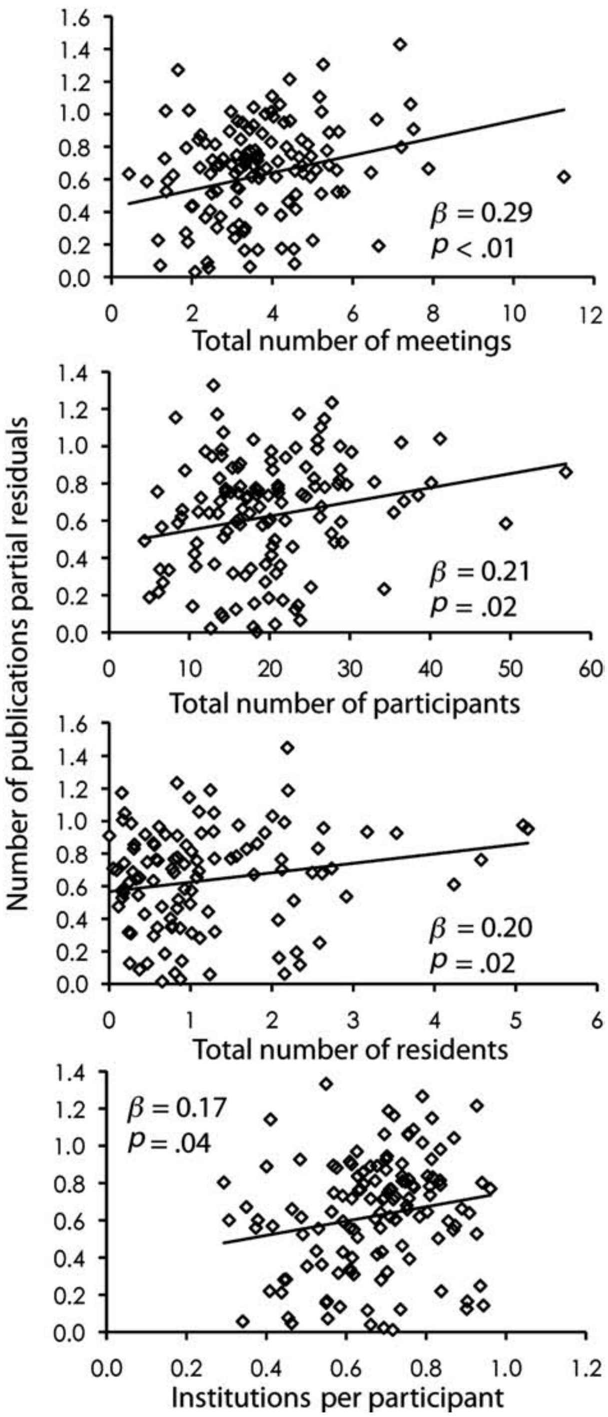

Figure 2. Partial residual plots of individual factors retained in the best model for predicting the total number of publications resulting from working groups. The best-fitting full-regression model ($r^2 = .33$, $p < .0001$) resulting from forward–backward selection among 24 potential predictors contained start date as a control variable (a negative effect, indicating that earlier groups have had more time for productivity; $p = .0088$), the total number of meetings ($p = .0024$), the total number of participants ($p = .0189$), the total number of residents ($p = .0216$), the number of institutions per participant ($p = .0409$), and the average meeting duration as a nonsignificant effect ($p = .4584$).

fellows) were also significantly more productive. Resident participants with past experience in synthetic research may imbue working groups with the expertise and skills distinctive to synthesis work, which may result in higher productivity. They may also help to mediate transitions between working group meetings by coordinating local events and maintaining research momentum until the group meets again.

Finally, contrary to the findings of all previous research, the groups involving collaborators from greater numbers of institutions were significantly more productive. Although the rising importance and frequency of cross-institutional collaborations has long been anticipated (Gibbons et al. 1994, Nowotny et al. 2001), findings have so far demonstrated that the more institutions involved in a collaboration, the less productive it will be (Cummings and Kiesler 2005, 2007). That negative correlation is largely due to the fact that the multi-institutional collaborations that were previously studied tended to be highly distributed geographically, and so they incur heavy coordination costs (e.g., planning phone conferences, frequent and inefficient exchanges of e-mails). Multi-institutional collaborations that share some qualities of the NCEAS working groups (e.g., democratic and flexible management, proximity, frequent face-to-face meetings) experience greater success (Corley et al. 2006). By collaborating in an environment in which the members of different institutions can meet face to face and that lowers coordination costs by enhancing the effectiveness of communication and trust building, synthesis groups appear able to harness the long-promised power of these unions for greater productivity.

As with working group productivity, the total number of working group meetings was the strongest predictor of a group's research impact (figure 3). In addition, the proportion of the total number of group members present at each meeting was positively associated with average citation rates (figure 3), which indicates the benefits of retaining consistent membership across meetings rather than inviting collaborators to participate only in particular group meetings. Presumably, the participants not only carry momentum and increase investment through this consistent engagement, but they also carry forward their experience in synthesis research.

Career effects

Collaboration is structured by broader disciplinary and organizational environments, and scientific careers are structured by collaboration (Hackett 2005, Shrum et al. 2007, Parker et al. 2010). In a field in which the primary professional society (the Ecological Society of America) has approximately 10,000 members, altering attitudes and practices of the 4,000 scientists who have participated in NCEAS activities may substantially contribute to changes in the scientific culture. Using two lines of evidence, our analyses suggest that the experience of engaging in synthesis in this environment has made these individuals more collaborative,

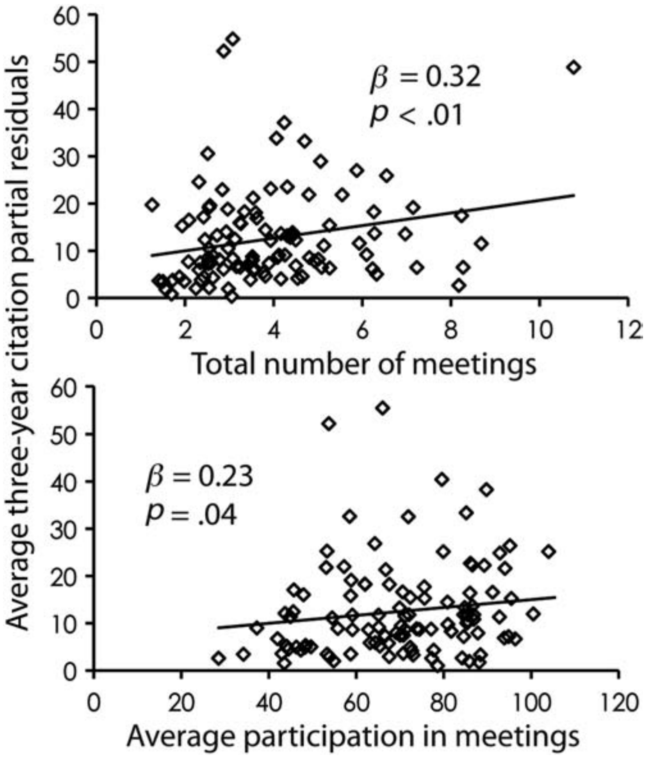

Figure 3. Partial residual plots of individual factors retained in the best-fitting model for predicting the average number of total citations within three years of publication for journal publications resulting from working groups. The best-fitting full-regression model ($r^2 = .11$, $p = .0064$*) resulting from forward–backward selection among 24 potential predictors contained the total number of meetings (*$p = .0046$*), the average percentage of the total number of participants at meetings (*$p = .0434$*), and a nonsignificant effect of the percentage of leaders among the participants (*$p = .0595$*).*

just as working group members had predicted in surveys (Hackett et al. 2008).

The effects of synthesis experience on working group participants. We compiled a database of publications by a subset of working group collaborators to determine whether working group participants' publication characteristics differed after their working group experience. We randomly selected 10 working groups and then examined the participants' ($N = 176$) bibliographies by consulting the Web of Science (*http://thomsonreuters.com/products_services/science/science_products/a-z/web_of_science*), the participants' personal Web sites, and their curricula vitae (when they were available online). This allowed us to compile the peer-reviewed journal articles produced by the working group participants ($N = 9282$).

Using the number of coauthors as an indicator of collaboration, we employed analyses of covariance to determine whether the publications produced by the working group participants averaged more authors after their visit to NCEAS. We used the *academic age* (the publication date of an article minus the date of the author's first publication listed in the Web of Science) as a covariate, expecting that the average number of coauthors would change across career stages, regardless of working group experience. The publication data were transformed with a *z*-score ((publication value − participant mean value)/participant value standard deviation) so that we could focus on how individuals change over time.

We used a subset of the publications for this analysis ($n = 1702$). The analysis excluded publications produced by authors at academic ages that were represented by fewer than three publications in the database overall and any publications on which more than one of our focal participants was an author, because these publications represent nonindependent data points. The publications produced by authors whose academic age was over 30 years were overwhelmingly published after their involvement in a working group and were therefore excluded. We restricted the analysis to publications from 1996 to 2003, because there is a strong effect of publication year on the number of authors, which reflects the recent trend toward team work in science (Wuchty et al. 2007); reducing the range of publication years reduces this effect and provides greater balance to research published before or after the authors' participation in a working group within years and age classes.

The analysis of the number of coauthors for each publication between 1996 and 2003 demonstrates that NCEAS working group participants were significantly more collaborative after coming to NCEAS (full-regression model, $p < .0001$). Positive effects of academic age ($p = .0033$) and working group experience ($p = .0099$) on the number of coauthors were evident, and there was no significant interaction for these effects (academic age × program participation (before vs after), $p = .1253$).

A comparison of synthesis-center postdocs with postdocs in traditional settings. We compared the research of past NCEAS postdoctoral fellows ($n = 22$) with that of past NSF bioinformatics postdoctoral fellows engaged in ecological projects ($n = 25$) who were funded within the same period (2000–2003). Bioinformatics postdoctoral fellows offer a meaningful comparison group because they engaged in types of research projects and shared an array of disciplinary expertise similar to those of the NCEAS postdoctoral fellows, but they were housed in more traditional research settings. As with working group participants, we collated the postdocs' publication records from Internet research. We examined the characteristics of their research output before (two years before the start of the postdocs' program, plus the first year of funding) and after their postdoctoral work had begun (the second, third, and fourth years).

We used a two-way analysis of variance (funding source × program participation) to determine whether and how the postdoc groups differed in terms of the quantity and impact of the research that they produced and how the groups changed during their postdoctoral experiences.

Our analysis revealed that although the NCEAS and bioinformatics postdocs were similar in productivity, the NCEAS postdocs were more collaborative after their postdoctoral training (figure 4). Overall, these groups did not significantly differ in the IF of the journals in which they published (full-regression model, $p = .4726$) or in the number of publications that they produced (full-regression model, $p = .1169$), although there was a slight trend for NCEAS postdoctoral associates to have more publications both before and after their postdoctoral tenure. Both groups of postdocs also published in high-visibility journals; the average IF of the journals in which they published (mean IF = 5.6) compares favorably with those of top ecology journals (e.g., *Ecological Monographs*, IF = 5.2; *Ecology*, IF = 4.9).

A visual inspection of the data (figure 4) revealed that the NCEAS postdoctoral associates accrued a greater number of citations in the three years following the publication of their postdoctoral papers. Recognizing that citations can be strongly influenced by the number of coauthors (Lokker et al. 2008), we included the number of coauthors as a predictor in the model (funding source × program participation × the number of authors). The number of authors was a highly significant predictor of the three-year accumulation of citations (the number of authors, $p < .0001$; program participation × the number of authors, $p = .0196$), and no other variables or combinations had a significant effect ($p > .20$) on the number of citations.

Indeed, the greatest difference between the NCEAS and the bioinformatics postdoctoral associates was the number of coauthors with whom they published after their postdoctoral work (full-regression model, $p < .0001$). After the postdoctoral experience, both groups published with more coauthors ($p < .0001$) than they had previously, but the NCEAS postdocs had significantly more coauthors ($p = .0006$), and the increase in coauthors for the NCEAS postdocs was substantially sharper (figure 4) than that for the bioinformatics postdocs, who worked in more traditional settings (funding × program participation, $p = .0449$).

Implications of the results

This study has implications for designing large-scale synthesis initiatives. Current-design models range from traditional research centers operating in a central location to initiatives with widely distributed participants. Our findings indicate that centralized synthesis centers can confer several specific benefits. Previous research on NCEAS working group social dynamics reported that face-to-face meetings in a neutral location were instrumental in developing the trust and communication efficiency that accelerate idea generation (Rhoten 2003, Hackett et al. 2008). Our findings demonstrate the importance that face-to-face interaction has had at a physical center. The number of meetings is the strongest predictor of working group productivity and scientific impact, even when one controls for a project's total length. This result suggests that the benefits supported by these meetings are not simply a matter of the time in which ideas are incubated but also of qualities conferred by the social interactions that meetings enable.

That the number of institutions involved in a working group has a significant positive effect on productivity further supports this interpretation. Despite growing calls for cross-institutional collaborations to advance scientific understanding and to solve complex social and environmental problems, the coordination costs associated with such initiatives have significantly decreased their potential productivity (Cummings and Kiesler 2005, 2007). Our data indicate the opposite relationship in NCEAS synthesis groups: previous sociological study of NCEAS working groups (Hackett et al. 2008) suggested that the efficiency, speed, and openness of communication in the working group structure serve to lower the coordination costs associated with interinstitutional collaborations and facilitate productive interactions. This result highlights the important role of this type of synthesis group for creating an arena in which fruitful interactions occur among diverse collaborators.

From an organizational-learning perspective, our most important finding is that center residents (postdoctoral and sabbatical fellows) significantly increased their productivity in synthesis groups. This finding may indicate that synthesis

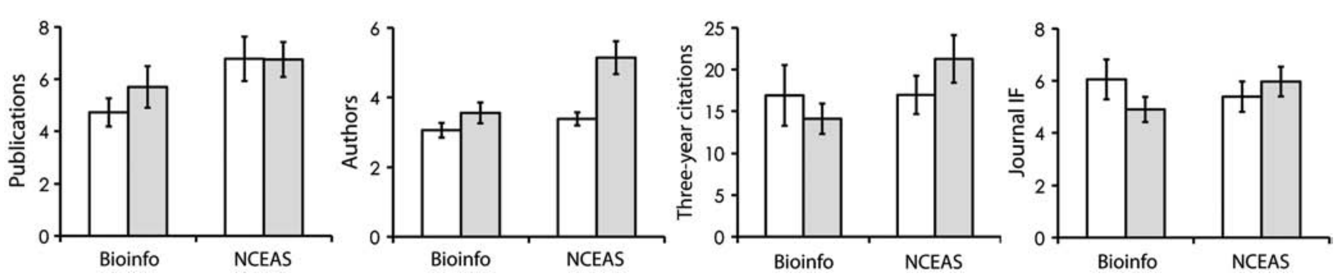

Figure 4. Average number of publications of past National Center for Ecological Analysis and Synthesis (NCEAS) postdoctoral fellows (n = 22), with past National Science Foundation bioinformatics (Bioinfo) postdoctoral fellows (n = 25) funded in the same period (2000–2003). We examined the characteristics of their research output before (two years before the start of their program, plus the first year of funding) and after (the second, third, and fourth years after the start of the program) their postdoctoral work had begun. Abbreviation: IF, impact factor.

is a distinct form of research benefiting from long-term experience and distinctive skills (Carpenter et al. 2009b). Such center residents are likely to transmit such expertise to working groups and across generations of residents, facilitating organizational learning within the synthesis center. Furthermore, as the residents move on, these experiences and skills may be transferred to students and colleagues, which may affect research far outside the confines of the synthesis center.

Our findings also provide guidance for designing and leading synthesis groups. Synthesis leaders should attempt to meet as often as possible in order to benefit from the generative social interactions that occur within this stimulating environment. As researchers and institutions increasingly move toward remote collaboration, a central challenge will be capturing the sociological aspects of face-to-face meetings that foster creativity, productivity, and serendipitous discovery. Synthesis groups will also benefit from involving participants with past experience in synthetic research. Although we did not find the expected diminishing returns with increased group size or number of institutions, common sense dictates that there are some upper limits to the number of individuals or institutions that can be successfully engaged in a project (Von Tunzelmann et al. 2003).

Finally, our findings indicate that group leaders should strive for cohesiveness and consistency in group composition over time. This suggestion is concordant with results of ethnographic work that highlighted the importance of trust building, emotional energy and group solidarity that facilitate productive group behaviors (Hackett et al. 2008). Box 1 provides a brief review of some aspects of the management of synthesis working group dynamics that are less amenable to quantitative analysis but that our experience and the sociological literature suggest are important considerations for group leaders. High variability in peer-reviewed publication production should also remind us that there are many metrics of success beyond these products and many influences not captured in our analyses.

Our work indicates that participation in synthetic research probably also has consequences for scientific careers and, ultimately, for scientific culture. The working group participants and resident researchers in our study became

Box 1. Managing synthesis working group dynamics.

Through the distillation of findings from qualitative studies of NCEAS working groups (Hackett et al. 2008, Hackett and Parker 2011), other sociological research, and the firsthand experiences of working group leaders, the following have proven to be important aspects of collaboration and leadership:

Encourage diverse viewpoints. The power of synthesis lies in its ability to tightly integrate beliefs or interpretations, which are often at odds with one another. The ability to incorporate such diversity can be inhibited by a focus on consensus building rather than testing, analyzing, and integrating diverse viewpoints too early in the process, which may lead to groupthink and false consensus (Janis 1972).

Manage power relations. Because of (often unstated) epistemological biases, some forms of expertise can be accorded more power and legitimacy in the collaborative context (e.g., physical over natural science or quantitative over qualitative). Collaborators must be conscious of these assumptions and must manage the power associated with different kinds of knowledge claims, not unduly allowing one perspective, method, or discipline to dominate (MacMynowski 2007).

Provide incentives for individual group members. Synthesis occurs at the interstices of well-defined research areas. However, because of the traditional scientific rewards system (founded on expertise-specific scientific contributions) or a simple lack of intrinsic interest in the synthetic topic, recruiting and retaining collaborators can prove challenging. Conscious efforts must be made to achieve collaborative parity, wherein the group produces scientific outcomes capable of advancing understanding through synthesis while also advancing individual careers (Parker 2006, Hackett and Parker 2011).

Establish clear expectations regarding data sharing, intellectual property, authorship, and other ethical considerations early on and periodically thereafter. Disciplinary cultures differ in regard to these topics (Osborne and Holland 2009), with tacit norms often requiring explanation. Junior colleagues can fare disproportionately poorly when such ethical dilemmas arise (e.g., receiving insufficient authorship credit; Lawrence 2002). Senior scientists, in particular, should be mindful of such issues and should manage them when necessary.

Build group cohesion. Collaboration is an emotional as well as intellectual act. Trust among collaborators and commitment to the group and its ideas are critical for overcoming epistemic and cultural barriers and for producing highly creative work (Collins R 1998, Farrell 2001). Engaging in informal interactions such as eating together, socializing, and developing group rituals can help build strong social bonds among collaborators (Hinds and Kiesler 2002, Parker 2006, Hackett et al. 2008). However, care must be taken so as not to inhibit the ability to fairly and frankly assess group work and so as not to exclude certain individuals from group-building activities.

Order the discussion. First, physical layout matters. For instance, more dominant individuals tend to choose more central seats, leading them to dominate conversations (Hare and Bales 1963, Stewart et al. 2007). Seating the group in a circle can help reduce this tendency. Second, group leaders must maintain a focused conversational direction while allowing the flexibility to capitalize on the serendipitous, potentially transformative ideas that emerge (Hackett et al. 2008). Smaller, task-specific breakout groups that periodically regroup and reintegrate can facilitate this dynamic. Finally, providing background materials before and "homework" between meetings allows concentrated focus on the most important and intellectually challenging tasks when meeting face to face.

more collaborative after participating in scientific synthesis. Because collaboration and the number of coauthors tend to increase research productivity and impact (Landry et al. 1996, Lee and Bozeman 2005), it may be tenably assumed that participation in synthesis can yield positive long-term effects on scientific careers. Furthermore, by providing opportunities for researchers to develop requisite experience and skills, synthesis centers ultimately contribute to the creation of a more collaborative and synthetic scientific culture, better able to transcend specialized ways of knowing and to improve scientific understanding.

As we look toward the horizon, we see that new technologies and new forms of media are changing the way scientists communicate. Collaborations are becoming more widely distributed (Olson et al. 2008), and the attraction of virtual organizations that use cyberinfrastruture to bridge physical distance is evident (Cummings et al. 2008). Virtual organizations reduce the expenses and constraints associated with a physical location, provide access to remote collaborators and equipment, and allow researchers enhanced independence and flexibility (Cummings et al. 2008, Noori et al. 2009). Virtual technologies are improving rapidly. It is possible to imagine a future in which physical synthesis centers are replaced by virtual organizations. At present, however, physical centers have important advantages. Face-to-face interactions improve the transmission of tacit knowledge (Polanyi 1966, Bechtel 1993, Collins HM 2001); role and identity formation (Nohria and Eccles 1992); communication (Olson and Olson 2000); and the development of the trust, cohesion, and commitment necessary for catalyzing and motivating intellectual work (Mullins 1972, Collins R 1998, Farrell 2001). Technological support and logistics become easier, and the accumulation of long-term experience by resident scientists and staff facilitates more short-term research projects. Physical centers also create a sense of gravitas and the associated expectations of quality (Hackett et al. 2008), which will be difficult to reconstruct virtually. Presently, synthesis centers, such as NCEAS, NESCent, and NIMBioS, blend virtual and proximate interaction in a hybrid form wherein distributed work is punctuated by intense face-to-face interactions. This tactic leverages the benefits of both research styles while reducing many of costs associated with each. Virtual technologies will increasingly be used in scientific synthesis. Until radical technological innovations more ably capture and duplicate the lived and embodied facets of collaboration and cultural shifts facilitate its adoption, our results suggest that face-to-face interaction will remain critical for success in synthesis.

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References cited

[AC-ERE] US National Science Foundation Advisory Committee for Environmental Research and Education. 2003. Complex Environmental Systems: Synthesis for Earth, Life, and Society in the 21st Century. US National Science Foundation.

[AC-ERE] US National Science Foundation Advisory Committee for Environmental Research and Education. 2009. Transitions and Tipping Points in Complex Environmental Systems. US National Science Foundation.

Babu AR, Singh YP. 1998. Determinants of research productivity. Scientometrics 43: 309–329.

Bechtel W. 1993. Integrating disciplines by creating new disciplines: The case of cell biology. Biology and Philosophy 8: 277–299.

Bell G, Hey T, Szalay A. 2009. Computer science: Beyond the data deluge. Science 323: 1297–1298.

Brown J, Carpenter S. 1993. National Center for Ecological Synthesis: Scientific Objectives, Structure, and Implementation. Report from a Joint Committee of the Ecological Society of America and the Association of Ecosystem Research Centers; 8 February 1993, Albuquerque, New Mexico.

Carlson S. 2006. Lost in a sea of science data. Chronicle of Higher Education 52: A35.

Carpenter SR, et al. 2009a. Accelerate synthesis in ecology and environmental sciences. BioScience 59: 699–701.

Carpenter SR, et al. 2009b. The Future of Synthesis in Ecology and Environmental Sciences. National Science Foundation.

Collins HM. 2001. Tacit knowledge, trust, and the Q of sapphire. Social Studies of Science 31: 71–85.

Collins R. 1998. The Sociology of Philosophies: A Global Theory of Intellectual Change. Harvard University Press.

Corley EA, Boardman PC, Bozeman B. 2006. Design and the management of multi-institutional research collaborations: Theoretical implications from two case studies. Research Policy 35: 975–993.

Cummings JN, Kiesler S. 2005. Collaborative research across disciplinary and organizational boundaries. Social Studies of Science 35: 703–722.

———. 2007. Coordination costs and project outcomes in multi-university collaborations. Research Policy 36: 1620–1634.

———. 2008. Who collaborates successfully?: Prior experience reduces collaboration barriers in distributed interdisciplinary research. Pages 437–446 in Begole B, McDonald DW. Proceedings of the 2008 ACM conference on computer supported cooperative work. ACM.

Cummings J[N], Finholt T, Foster I, Kesselman C. 2008. Beyond Being There: A Blueprint for Advancing the Design, Development, and Evaluation of Virtual Organizations. National Science Foundation.

Farrell MP. 2001. Collaborative Circles: Friendship Dynamics and Creative Work. University of Chicago Press.

Fava GA, Ottolini F. 2004. International trends in psychiatric research. A citation analysis. Current Opinion in Psychiatry 17: 283–287.

Gibbons M, Limoges C, Nowotny H, Schwartzman S, Scott P, Trow M. 1994. The New Production of Knowledge: The Dynamics of Science and Research in Contemporary Societies. Sage.

Hackett EJ. 2005. Essential tensions: identity, control, and risk in research. Social Studies of Science 35: 787–826.

Hackett EJ, Parker JN. 2011. Leadership of scientific groups. In Sims Bainbridge W, ed. Leadership in Science and Technology: A Reference Handbook. Sage. Forthcoming.

Hackett E[J], Parker J[N], Conz D, Rhoten D, Parker A. 2008. Ecology Transformed: The National Center for Ecological Analysis and Synthesis and the Changing Patterns of Ecological Research. Pages 277–296 in Olson GM, Zimmerman A, Bos N. Scientific Collaboration on the Internet. Massachusetts Institute of Technology.

Hare AP, Bales RF. 1963. Seating position and small group interaction. Sociometry 26: 480–486.
Hinds P, Kiesler S. 2002. Distributed Work. MIT Press.
Janis IL. 1972. Victims of Groupthink: A Psychological Study of Foreign-policy Decisions and Fiascoes. Houghton Mifflin.
Kim S-H. 2005. Explaining scientific productivity variation. Pages 1032–1035 in EDS. KORUS 2005: Proceedings of the 9th Russian–Korean International Symposium on Science and Technology. KORUS.
Kostoff RN. 2002. Overcoming specialization. BioScience 52: 937–941.
Landry R, Traore N, Godin B. 1996. An econometric analysis of the effect of collaboration on academic research productivity. Higher Education 32: 283–301.
Lawrence PA. 2002. Rank injustice. Nature 415: 835–836.
Leahey E. 2007. Not by productivity alone: How visibility and specialization contribute to academic earnings. American Sociological Review 72: 533–561.
Lee S, Bozeman B. 2005. The impact of research collaboration on scientific productivity. Social Studies of Science 35: 673–702.
Lokker C, McKibbon KA, McKinlay RJ, Wilczynski NL, Haynes RB. 2008. Prediction of citation counts for clinical articles at two years using data available within three weeks of publication: Retrospective cohort study. British Medical Journal 336: 655–659.
Long JS. 1992. Measures of sex differences in scientific productivity. Social Forces 71: 159–178.
Lotka AJ. 1926. The frequency distribution of scientific productivity. Journal of the Washington Academy of Sciences 16: 317–324.
MacMynowski DP. 2007. Pausing at the brink of interdisciplinarity: Power and knowledge at the meeting of social and biophysical science. Ecology and Society 12: 20.
Mullins NC. 1972. The development of a scientific specialty: phage group and the origins of molecular biology. Minerva 10: 51–82.
Neter J, Kutner MH, Wasserman W, Nachtsheim CJ. 1996. Applied Linear Regression Models. McGraw-Hill.
Nohria N, Eccles RG. 1992. Face to face: Making network organizations work. Pages 288–308 in Nohria N, Eccles RG, eds. Networks and Organizations: Structure, Form, and Action. Harvard Business School Press.
Noori S, Hosseini SH, Baksha A. 2009. Human performance factors in the evaluation of virtual organizations. International Journal of Business Management 4: 41–49.
Nowotny H, Scott P, Gibbons M. 2001. Re-Thinking Science: Knowledge and the Public in an Age of Uncertainty. Polity.
Olson GM, Olson, JS. 2000. Distance matters. Human–Computer Interaction 15: 139–178.
Olson GM, Zimmerman A, Bos N, eds. 2008. Scientific Collaboration on the Internet. MIT Press.
Osborne JW, Holland A. 2009. What is authorship, and what should it be? A survey of prominent guidelines for determining authorship in scientific publications. Practical Assessment Research Evaluation 14: 1–19.
Parker JN. 2006. Organizational Collaborations and Scientific Integration: The Case of Ecology and the Social Sciences. PhD Dissertation. Arizona State University, Tempe.
Parker JN. 2010. Integrating the social into the ecological: Organizational and research group challenges. Pages 85–110 in Parker JN, Vermeulen N, Penders B, eds. Collaboration in the New Life Sciences. Ashgate.
Parker JN, Vermeulen N, Penders B, eds. 2010. Collaboration in the New Life Sciences. Ashgate.
Patra SK, Mishra S. 2006. Bibliometric study of bioinformatics literature. Scientometrics 67: 477–489.
Pickett STA, Kolasa J, Jones CG. 2007. Ecological Understanding: The Nature of Theory and the Theory of Nature, 2nd ed. Academic Press.
Polanyi M. 1966. The Tacit Dimension. University of Chicago Press.
Price DJDS. 1963. Little Science, Big Science. Columbia University Press.
Rhoten D. 2003. A Multi-method Analysis of Social and Technical Conditions for Interdisciplinary Collaboration. National Science Foundation. Report no. BCS-0129573.
ScienceWatch. 2009. Climate Change. (15 August 2011; *http://sciencewatch.com/ana/st/climate*)
Shrum W, Chompalov I, Genuth J. 2001. Trust, conflict and performance in scientific collaborations. Social Studies of Science 31: 681–730.
Shrum W, Genuth J, Chompalov I. 2007. Structures of Scientific Collaboration. MIT Press.
Stewart DW, Shamdasani PN, Rook DW. 2007. Focus Groups: Theory and Practice. Sage.
Von Tunzelmann N, Ranga M, Martin B, Geuna A. 2003. The Effects of Size on Research Performance: A SPRU Review. University of Sussex at Brighton.
Wilson EO. 1998. Consilience: The Unity of Knowledge. Random House.
Wuchty S, Jones BF, Uzzi B. 2007. The increasing dominance of teams in production of knowledge. Science 316: 1036–1039.

Stephanie E. Hampton (hampton@nceas.ucsb.edu) is a freshwater biologist and deputy director of the National Center for Ecological Analysis and Synthesis at the University of California, Santa Barbara, where sociologist John N. Parker is a postdoctoral associate. Parker is also affiliated with Barrett, The Honors College at Arizona State University, in Tempe.