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Synthesis

How coupled is coupled human-natural systems research?

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ABSTRACT. Interdisciplinary research that links human and natural systems is critical to addressing complex environmental and ecological problems. A growing number of interdisciplinary research teams investigate coupled natural-human systems, but the degree to which they actually examine two-way linkages between the systems is limited. We examined aspects of interdisciplinary teams that were explicitly funded to conduct research including such linkages by considering attributes of team leaders, team members, and analysis methods employed. Our objective was to investigate the degree to which interdisciplinary teams studying coupled natural-human systems publish research that displays two-way linkages between systems. Our analysis shows that team members' academic disciplines and the types of analysis methods that interdisciplinary teams apply play a crucial role in the success of the team in publishing articles that include two-way linkages. We found that the success of developing two-way linkages is enhanced when teams include leaders and/or members from interdisciplinary academic disciplines (e.g., planning departments, sustainability, environmental economics, biological and ecological engineering, and individuals affiliated with more than one academic department from different discipline categories). Additionally, the presence of social science members increases the likelihood of two-way linkages, whereas the presence of physical science or biological/life science members decreases this likelihood. Among articles that included two-way linkages, essentially all utilized a conceptual-/literature-review approach, or included simulation model analysis. Based on these findings, we conclude that interdisciplinary teams are not a mere sum of people from different academic disciplines, but a group of people who have the ability to incorporate different disciplines conceptually and analytically. To move forward, it is important to acknowledge that becoming an interdisciplinary researcher takes deliberative work. Educational programs that train students and early career scholars with flexible thinking and analytical capacities may be the key to furthering coupled natural-human systems research.

Key Words: *coupled natural-human systems research; interdisciplinary research team; science of team science; social-ecological sustainability; two-way linkages*

INTRODUCTION

Humans are a dominant force on earth, interacting strongly with the planet's natural systems. Models that account for these coupled interactions between humans and nature are necessary for realistic projections of the trajectory of our planet. The growth of social-ecological sustainability science over the past decades has led to increased efforts by scientists to investigate interactions within coupled human-natural systems (Hummel et al. 2013). Coupled natural-human system models refer to integrated systems where humans and nature interact (Liu et al. 2007). Coupled natural-human system models account for simultaneous changes of ecological and human properties. For instance, human efforts to reduce carbon emissions play a key role in limiting temperatures rising in a natural system. Temperature normalization that reduces extreme natural disasters ultimately improves human well-being. Understanding those simultaneous changes is useful for examining issues such as climate change, biodiversity loss, ecosystem sustainability, and land-use change (Carroll et al. 2007, DeFries et al. 2007, Walsh et al. 2008, Bachelet et al. 2011). This integrative approach to earth system research can ultimately provide insights into new sustainability policy directions that enhance both ecological and human well-being. Despite such recognition, investigating coupled natural and human systems remains challenging in practice because of their complex nature and associated high levels of uncertainty (Carroll et al. 2007, Xiang 2013).

A primary goal of research on coupled natural-human systems is to represent and analyze the linkages between the two systems, rather than only one-way impacts from the natural system to the human system or from the human system to the natural system. These two-way linkages play a crucial role in capturing potential non-linearities, time lags, and thresholds of system changes (Hull et al. 2015). They can also lead to changes in the overall condition of natural and human systems at a wide range of timescales, from hours to decades. A small change in a natural (or human) system could cause a cascading impact on the other system within a short time. Each system can adapt to the changing conditions both within its own system and across the counterpart system, leading to a dynamic and constantly evolving overall system. These complexities have made it challenging for scientists to identify and quantify these two-way linkages (DeFries et al. 2007, Gopalakrishnan et al. 2018). In response to this challenge, scientists have formed interdisciplinary collaborations across diverse fields (Stokols et al. 2008, Trochim et al. 2008, Börner et al. 2010). By integrating various theories, concepts, data, and methodologies, they employ novel approaches and arrive at solutions beyond the scope of a single study area (National Academy of Sciences 2005). In many ways, the development of this field is an example of convergence research, leading to new insights (National Research Council 2014).

As interdisciplinary research has grown, the science of team science (SciTS) has also expanded. SciTS aims to promote understanding of interdisciplinary research teams and to support scientific progress by examining behavioral and management strategies (Stokols 2008, Börner et al. 2010, Falk-Krzesinski et al. 2011, Norris et al. 2016, Hall et al. 2018). Developing an effective

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interdisciplinary research team requires individual and team efforts to overcome challenges, including identifying appropriate expertise of team members to most effectively advance the project (Norris et al. 2016), narrowing cognitive gaps among members to create and share a common conceptual framework to solve research questions (Stokols et al. 2008), and identifying institutional support and professional development programs (Falk-Krzesinski et al. 2011). Recent research emphasizes a significant role of leadership in teams to achieve a high performance (Palmer 2018, Boone et al. 2020). If done well, these efforts contribute to enhancing both future team performance and intellectual progress across different fields (Bishop et al. 2014).

Our study evaluates the degree to which interdisciplinary research teams studying coupled natural-human systems publish research that displays two-way linkages between systems and examines how this is associated with attributes of team leaders and members. Past studies have generally assessed interdisciplinary team performance by measuring research outputs, such as the number of publications, the publication impact, or the number of citations (see a review in Hall et al. 2018). Understanding the academic disciplines of team leaders and members is important because they are the ones who collaborate to design and produce research products (Van Rijnsoever and Hessels 2011). However, there is little research addressing the relationship between academic disciplines of team members and the degree to which their studies examine dynamic feedback between coupled natural and human systems. In this study we address the following questions. First, to what degree are two-way linkages included in coupled natural-human system research? Second, what academic disciplines of team leaders and members are important predictors for the achievement of two-way linkages in the research? Third and last, what analysis methods most affect the achievement of two-way linkages? We answer these questions by assessing peer-reviewed publications produced by teams funded through the National Science Foundation's (NSF) formerly named Dynamics of Coupled Natural and Human Systems (CNH) grants (in 2019 the CNH program was renamed the Dynamics of Integrated Socio-Environmental Systems, or DISES, program; see https://www.nsf.gov/pubs/2020/nsf20579/nsf20579.htm).

METHODS

Data collection

We collected data on interdisciplinary teams funded through the competitive NSF-CNH program, i.e., grant awards established through NSF 06-587, 07-598, and 10-612. Unlike other representative funding programs on studies of coupled human-natural systems, only the NSF-CNH program had the intent of investigating coupled human and natural systems without limitation of any particular field (see Table 1 in Liu et al. 2007). From 2001 to 2020 the CNH programs promoted projects that investigated the complex interactions within and among environmental and human components. This program emphasized producing studies of fully coupled natural and human systems, rather than of two discrete systems, with explicit analysis of the processes and dynamics between the natural and human components.

We sampled 14.3% of funded projects (grant awards) from each year between 2001 and 2018 (one to four grant awards per year, totaling 44 out of 310 total grant awards). First, we assigned random numbers to each grant in each year. Then we selected the first one to four grants (14% from the total number of grants in each year, minimum = one, median = two, and maximum = four). Next, we examined peer-reviewed journal articles resulting from the 44 sampled grant awards as listed on the NSF webpage (see CNH search results at https://www.nsf.gov/awardsearch/simpleSearchResult?queryText=CNH&ActiveAwards=true&ExpiredAwards=true). Each grant award published between zero to 63 articles (mean = 9.4 articles, median = three articles). For the six grant awards that produced more than 20 publications, we randomly selected 20 articles. For the 10 grant awards that did not report any publications on the NSF webpage, we searched Google Scholar using keywords "National Science Foundation" and the exact grant award number to identify any publications supported by that grant award. Only one of these grant awards had any associated publications, and these were included in the sample. The final sample included 241 articles for analysis.

Coding and creation of variables

The authors developed a coding-criteria manual to determine which information from each article should be coded in each category. The coding manual included examples of each category (see Table A 1.1 in Appendix 1 for the coding criteria). The categories coded for each article included (1) the academic disciplines of Principal Investigators (PIs); (2) the academic disciplines of participating authors; (3) the analysis method used in the article; and (4) the degree of coupling in the article, i.e., two-way linkages, one-way linkages, or incomplete linkages. We also noted whether each grant-award team produced at least one article demonstrating two-way linkages.

Then the lead author read each of the articles and evaluated their content. For the purposes of this analysis, we defined team leaders as the grant award PIs and considered all additional participating authors as team members in the awarded team. We realize that these assumptions may not incorporate all leaders, and that some co-authors may not have actively participated in the underlying grant-award team. PI and author disciplines were determined by the primary academic department they were affiliated with at the time of the publication. The departments were coded to fit within six mutually exclusive discipline categories: biological/life science, social science, physical science, computer science/math/engineering, interdisciplinary, or undefined (see Table A 1.1 in Appendix 1). If PIs or authors were affiliated with multiple academic departments under different discipline categories, they were assigned to the interdisciplinary category. However, if they were affiliated with one academic department and also with a research center, they were categorized by their academic department. For all analyses regarding authors' disciplines, we excluded the category of "undefined" because these individuals were unable to be classified and were very rare (n = six authors, 0.4%). No PIs were categorized as "undefined."

In addition to coding for each PI and author discipline, we also calculated the diversity of PI disciplines within each grant award and the diversity of author disciplines within each article. The diversity score was calculated using the Shannon diversity index (H'), which accounts for both the number of discipline categories and dominance/evenness of those categories (Spellerberg and Fedor 2003). For example, if one article had five biological/life-science authors and two social-science authors, and another article had three biological/life-science authors and four social-science authors, the second article would be rated as more diverse. The index H' for diversity of authors or diversity of PIs will range from zero to 1.60, with higher scores indicating greater diversity.

The type of analysis method applied in each article was coded to fit within six mutually exclusive categories: conceptual/literature review, statistics, spatial analysis, mathematical analysis, simulation model analysis, and other (see Table A 1.1 in Appendix 1). A few articles applied multiple analytical methods. In these cases, we coded the analysis method applied to produce the final result only. For example, if a simulation model analysis used statistical analysis results as input data, we coded the article as simulation model analysis.

Degree of coupling in the research was coded using "yes/no" for the following linkages: one-way linkage from natural to human system, one-way linkage from human to natural system, two-way linkages between natural and human systems (see Table A 1.1 in Appendix 1). For example, if an article investigates the impact of industrial policy to limit carbon emissions on improvement of air quality, the direction from human to natural system is coded "yes" and the direction from natural to human system is coded "no". As a result, this article analyzes a one-way linkage. If this article also includes a linkage from how the improved air quality, in turn, decreases health-insurance costs, this article is coded as a two-way linkage because it also has a linkage from the natural to human system. We use the term "two-way linkage" to describe projects that include at least one effect in each direction. We have chosen not to use the term "feedback" because it is a more constrained term that may also imply there is a detailed structure of the back-and-forth interaction between the processes. If both one-way linkages were coded as "no," then the article was labeled as including no linkages. Articles with no linkages investigate either the natural or human system alone. This research is still important because it can lead to a deeper understanding of one system that provides the basis for linkages with the counterpart system (Pohl et al. 2015). For a majority of the analyses, we grouped all articles with no linkages and with one-way linkages into the "incomplete linkage" category. We coded a two-way linkage article as one and an incomplete linkage article as zero for these analyses. We also conducted analyses comparing articles with no linkages, one-way linkages, and two-way linkages (included in Table A 1.3 and 1.4 in Appendix 1). In these cases, we coded no linkage as one, one-way linkage as two, and two-way linkage as three.

Two researchers independently coded 36 articles (16% of our sample) for authors' disciplines, analysis methods, and linkages directions. Intercoder reliability calculations ranged from 82% to 100% agreement with Cohen's Kappa between 0.72 to 1.00 (see Table A 1.2 in Appendix 1), indicating satisfactory agreement (McHugh 2012).

Analysis plan

First, we conducted a Bayesian hierarchical logistic regression analysis. This allowed examination of how all team and article attributes (predictor variables: PIs' academic disciplines, authors' academic disciplines, diversity of PIs' disciplines within a grant award, diversity of authors' disciplines within an article, and analysis method) predict the probability of an article including two-way linkages (dependent variable). This also checks the nested effects of grant awards to examine whether certain grants were more likely to produce two-way linkage articles. The classification of all articles by whether or not they include two-way linkages is given by the random variable Y, which has a Bernoulli probability with parameter Θ, where Θ is the probability that Y = 1 indicating that the article contains two-way linkages. The parameter Θ takes into account all team and article attributes, including authors' and PIs' academic disciplines, author and PI diversity indices, and analysis method. We included team and article attributes using a linear model without interactions on a logit scale for Θ, e.g., for a logistic regression. We modeled the effect of individual grant-awards teams using a Bayesian hierarchical model where each team had a random effect modeled as coming from a normal distribution with a M = zero and SD as a hyperparameter. We used non-informative prior distributions for all parameters in our Bayesian model (see details of independent covariates in Table 1).

We then examined the association between the inclusion of two-way linkages and each of the research team and article attributes individually by conducting several sets of statistical tests. When examining the relationship between the academic disciplines of PIs and of participating authors, or the analysis method of an article's inclusion of two-way linkages, chi-square tests were conducted. This included a standard chi-square test, post hoc tests based on residuals using the Bonferroni p adjustment method, and a resampling chi-square test based on permutations of the observed data. The data were permuted with replacement 10,000 times, calculating the test statistic for each permutation, and then comparing our observed test statistics to the distribution of the permuted test statistics to determine significance. When examining the relationship between the diversity of PIs' academic disciplines or diversity of authors' academic disciplines with the inclusion of two-way linkages, we conducted analysis of similarities (ANOSIM) tests. ANOSIM is similar to an ANOVA, but it is a non-parametric test of the significance of dissimilarities between two or more groups. It provides an R-value, a ratio of the between-groups variation (between two-way and incomplete linkages articles) to the within-group variation. An R-value is constrained between the values minus one to one. Closer to one suggests dissimilarity between groups in terms of group compositions and closer to zero suggests no difference between within-group variation and between-groups variation. Negative R values suggest more similarity between groups than within a group (Clarke 1993, Warton et al. 2012). The dissimilarity was measured by Bray-Curtis using R, and the data were permuted with replacement 9999 times, calculating the test statistic for each permutation, and then comparing our observed test statistics to the distribution of the permuted test statistics to determine significance.

Finally, a regression tree analysis (Michaelsen et al. 1994) was conducted including all of the research team and article attributes as predictor variables (PIs' academic disciplines, authors' academic disciplines, diversity of PIs' disciplines within a grant award, diversity of authors' disciplines within an article, and analysis method) to identify which attributes most successfully predicted whether an article contained two-way linkages (dependent variable). A regression tree analysis shows what

Table 1: Bayesian hierarchical logistic regression analysis demonstrating the relationship between team and article attributes and likelihood of articles including two-way linkages

Predictor Variable	B (Log Odds Ratios)	*SE (B)*	Exp(B) (Odds Ratios)	Lower 90% CI (5% quantile)	Upper 90% CI (95% quantile)
Analysis Methods					
Conceptual/ Literature Review	3.03	4.16	20.70	-12.30	1.36
Mathematical Analysis	3.41	4.15	30.27	-3.39	10.27
Simulation Model Analysis	2.96	4.08	19.30	-3.77	9.73
Spatial Analysis	-7.58	6.81	< 0.001	-19.84	2.50
Statistics	-1.07	4.16	0.34	-7.91	5.78
Other	-6.22	7.14	< 0.001	-18.91	4.48
Authors' Disciplines & Diversity					
Biological/Life Science	-0.03	0.11	0.97	-0.21	0.15
Social Science	0.18	0.32	1.20	-0.36	0.70
Physical Science	-1.18	0.54	0.31	-2.12	-0.35
Computer Science/Math/Engineering	-0.18	0.24	0.84	-0.62	0.17
Interdisciplinary	0.27	0.13	1.31	0.06	0.50
Authors' Discipline Diversity (Shannon Index)	2.51	0.99	12.30	0.95	4.18
PIs' Disciplines & Diversity					
Biological/Life Science	-0.53	0.43	0.59	-1.26	0.14
Social Science	-1.86	0.83	0.16	-3.33	-0.64
Physical Science	-1.09	1.22	0.34	-3.16	0.85
Computer Science/Math/Engineering	3.72	1.81	41.26	0.96	6.86
Interdisciplinary	0.22	0.61	1.25	-0.83	1.17
PIs' Discipline Diversity (Shannon Index)	0.32	1.86	1.38	-2.70	3.41

combinations of the team and article attributes lead to a higher skill in identifying articles that include two-way linkages. Each leaf of the tree identifies the combination of attributes that lead to a particular proportion of all articles which contain two-way linkages. Factors that predict end tree outcomes closer to zero are factors that reduce probability of two-way linkages and factors that predict end tree outcomes closer to one are factors that increase probability of two-way linkages.

We used R 1.1.456 (R Foundation 2021) to conduct Bayesian hierarchical logistic regression analysis (package: rethinking, nimble, and coda), conduct chi-square tests and post chi-square tests (package: chisq.posthoc.test), calculate the Shannon diversity index (package: QSutils), conduct the ANOSIM test (package: vegan), and conduct the regression tree analysis (package: rpart, rpart.plot).

RESULTS

Of 44 sampled grant awards, 38.6% (*n* = 17) of teams published at least one article including two-way linkages, and the rest of the teams did not. Those 17 teams either produced one or two articles with two-way linkages. Of 241 sampled articles, publications including two-way linkages accounted for 13.3% (*n* = 32). Publications demonstrating incomplete linkages accounted for 86.7% (*n* = 209): 15.3% (*n* = 32) with a one-way linkage from the natural to the human system, 30.6% (64) with a one-way linkage from the human to the natural system, and 46.9% (*n* = 113) with no linkage between systems.

Bayesian hierarchical logistic regression analysis

We conducted Bayesian hierarchical logistic regression analysis to examine which team and article attributes are more likely to include two-way linkages, while accounting for the random effects of individual grant awards. The magnitude of the random effects across the sampled grant awards were small when compared to the other team and article attributes (See Fig. A 1.1 in Appendix 1). This indicates that the grant awards do not cause significant effects after accounting for the team and article attributes.

In this regression, the analysis methods used in articles show large effects in terms of odds ratios, but there was also considerable uncertainty in these parameter estimates (see Table 1 and Fig. A 1.2 in Appendix 1). The odds ratios indicate that conceptual/ literature review, mathematical analysis, and simulation model analysis were all associated with great increased probability of two-way linkages whereas spatial analysis, statistics, and "other" were associated with a greatly decreased probability, although the 90% credible intervals overlapped with zero. Additionally, certain PI and author disciplines have a higher propensity to lead to articles with two-way linkages, and there is less uncertainty in these parameter estimates (See details in Table 1 and Figs. A 1.3 and A 1.4 in Appendix 1). Although more computer science/math/ engineering PIs predict greater likelihood of two-way linkages, more social science PIs predict lower likelihood of two-way linkages. When examining authors, more interdisciplinary authors predict greater likelihood of two-way linkages and more physical science authors predict lower likelihood of two-way linkages. Additionally, greater diversity of authors' disciplines was also an important predictor of greater likelihood of articles including two-way linkages.

Chi-square and ANOSIM tests

When examining the role of PI characteristics, our results show no association between PIs' specific disciplines and whether that

Table 2. Observed values and expected values demonstrating the relationship between authors' disciplines and likelihood of articles including two-way linkages. Obs. = Observed number; Exp. = Expected number

	Biological/Life		Social Science		Physical Science		Computer Science/ Math/ Engineering		Interdisciplinary		Total
	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	
Incomplete Linkage	588 (42.1%)	565.4 (40.4%)	77 (5.5%)	85.6 (6.1%)	135 (9.7%)	120.4 (8.6%)	76 (5.4%)	76.3 (5.5%)	309 (22.1%)	337.4 (24.1%)	1185 (84.8%)
Two-Way Linkage	79 (5.7%)	101.6 (7.3%)	24 (1.7%)	15.4 (1.1%)	7 (0.5%)	21.6 (1.5%)	14 (1.0%)	13.7 (1.0%)	89 (6.4%)	60.6 (4.3%)	213 (15.2%)
Total	667 (47.7%)		101 (7.2%)		134 (10.2%)		90 (6.4%)		398 (28.5%)		1398 (100%)

team produced at least one article demonstrating two-way linkages ($\chi^2 = 3.69$, df = 4, $p = 0.45$), and no significant difference between sampled chi-squares and the chi-square of the observed data ($p = 0.47$). Even though PIs' disciplinary diversity was greater in teams that produced at least one article demonstrating two-way linkages ($H' = 1.21$) than teams that produced incomplete linkage articles only ($H' = 0.91$), it was not significantly different, ANOSIM $R = -0.01$, $p = 0.47$. We assume that it is because almost a half ($n = 19$, 43.2%) of the teams sampled were led by PIs from a single discipline, although many included PIs from two different disciplines ($n = 19$, 43.2%) or three or more disciplines ($n = 6$, 13.6%).

When examining the role of author characteristics, there was a significant association between the numbers of authors from specific disciplines and the likelihood of articles including two-way linkages ($\chi^2 = 38.96$, df = 4, $p < 0.001$) as well as a significant difference between the sampled chi-squares and the chi-square of the observed data ($p < 0.001$). Three academic disciplines were significantly associated with the likelihood of two-way linkages (see Table 2). Biological/life science authors (Residuals = 3.37, $p = .007$) and physical science authors (Residuals = 3.61, $p = 0.003$) were more likely to be involved in incomplete linkage articles and less likely involved in two-way linkage articles. Alternately, interdisciplinary authors (Residuals = -4.68, $p < 0.001$) were less likely to be involved in incomplete linkage articles and more likely involved in two-way linkage articles. Computer science/math/engineering authors and social science authors were unrelated to articles with two-way linkages, $p > .13$. Diversity of authors' academic disciplines was not significantly higher for articles with two-way linkages ($H' = 1.39$) than for articles with incomplete linkages ($H' = 1.24$), ANOSIM $R = 0.01$, $p = .44$.

When examining the analysis method used in articles, there was a significant association between the analysis method and the likelihood of articles including two-way linkages ($\chi^2 = 26.03$, df = 5, $p < 0.001$) as well as a significant difference between the sampled chi-squares and the chi-square of the observed data ($p < 0.001$). Statistics were the most popular analytical method in the articles, followed by simulation model analysis and conceptual/literature review (Table 3). For articles demonstrating two-way linkages ($n = 32$), conceptual/literature reviews (50%) and simulation model analysis (34.4%) were major methods. Articles that used statistics were more likely to include incomplete linkages and less likely to include two-way linkages (Residuals = -3.73, $p = 0.002$). Alternately, conceptual/literature review articles were less likely to include incomplete linkages and more likely to include two-way linkages (Residuals = 3.77, $p = .002$). The other analysis methods (spatial analysis, mathematical analysis, simulation model analysis, and "other") did not lead to significant differences in the likelihood of articles including two-way linkages, $p > .65$.

As an additional exercise, we also conducted the same chi-square and ANOSIM tests examining how each team or article attribute related to degree of coupling when all three linkage types were examined (see Supplemental Analyses, Table A 1.3, and Table A 1.4 in Appendix 1). Overall, the results are similar to the above analyses that considered only incomplete linkages versus two-way linkages. The one notable difference in team and article attributes is that social science authors were marginally less associated with no linkage articles when the incomplete linkages were separated. This difference may arise because social science authors tend to participate in fewer no-linkage articles but somewhat more in one-way linkage articles.

Regression tree analysis

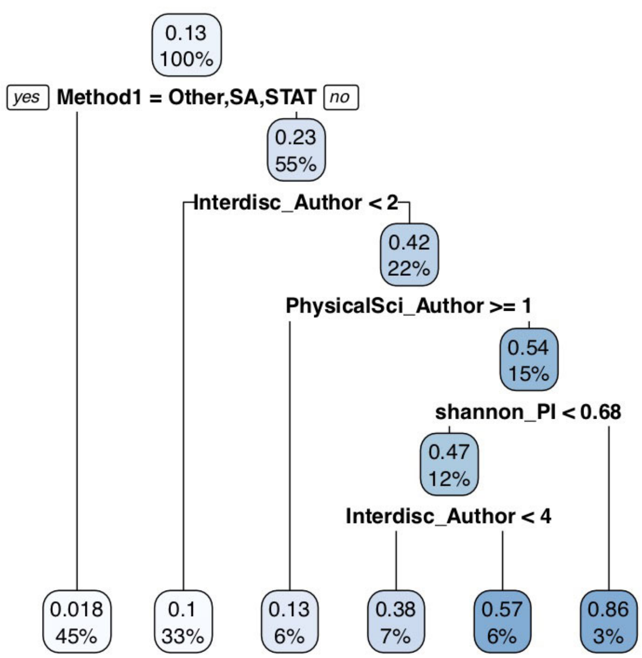
A regression tree analysis was conducted to examine which team and article attributes played the strongest role in predicting which articles include two-way linkages. The regression tree split into six branches (root node error: 0.12) based on five attributes: (1) analysis method; (2) the number of authors from the interdisciplinary discipline; (3) the number of authors from the physical science discipline; (4) diversity of PIs' disciplines; and (5) the number of authors from the interdisciplinary discipline again (Fig. 1).

The first branch splits by the analysis method used in an article. Articles that utilize spatial analysis, statistics, or "other" methods almost entirely produce articles with incomplete linkages between the natural and human systems. On the other hand, the use of conceptual/literature review, simulation model analyses, or mathematical analyses increases the possibility of developing two-way linkages within the article. In articles with fewer than two interdisciplinary authors or with one or more authors from physical science, our results show little likelihood of including two-way linkages. In contrast, articles with two or more interdisciplinary authors, no physical science authors, and that include a more diverse team of PIs (higher than 0.68 Shannon diversity index for PIs' disciplines) have the highest fraction (0.86) of two-way linkages ($n = 7$ articles, 3%). In cases in which a team has less diverse PIs, a team requires five or more authors from interdisciplinary disciplines to get the second highest fraction (0.57) of articles with two-way linkages ($n = 14$ articles, 6%).

Table 3: Observed values and expected values demonstrating the relationship between analysis methods and likelihood of articles including two-way linkages. Obs.=Observed number; Exp.=Expected number

	Conceptual/ Literature Review		Statistics		Spatial Analysis		Mathematical Analysis		Simulation Model Analysis		Other		Total
	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	
Incomplete Linkages	41 (17.0%)	49.4 (20.5%)	84 (34.9%)	74.5 (30.9%)	22 (9.1%)	19.1 (7.9%)	8 (3.3%)	9.5 (4%)	53 (22.1%)	55.5 (23%)	1 (0.4%)	0.9 (0.4%)	209 (86.7%)
Two-Way Linkages	16 (6.6%)	7.6 (3.1%)	2 (0.8%)	11.5 (4.7%)	0 (0%)	2.9 (1.2%)	3 (1.2%)	1.5 (0.6%)	11 (4.6%)	8.5 (3.5%)	0 (0.0%)	0.1 (0.1%)	32 (13.3%)
Total	57 (23.7%)		86 (35.7%)		22 (9.1%)		11 (4.6%)		64 (26.6%)		1 (0.4%)		241 (100%)

Fig. 1. Regression tree analysis. Combinations of team and article attributes will be closer to one (darker blue box) as the likelihood of two-way linkages increases. For all rows, "Yes" is on the left and "No" is on the right. The first row indicates analysis method (Method1): "Yes" indicates SA = spatial analysis, STAT = statistics, or "other"; "No" indicates conceptual/literature review, simulation model analysis, and mathematical analysis. The second row indicates the number of interdisciplinary authors (Interdisc_Author): "Yes" indicates fewer than two and "No" indicates two or more. The third row indicates the number of physical science authors (PhysicalSci_Author): "Yes" indicates more than one and "No" indicates zero. The fourth row indicates the Shannon index of PIs (shannon_PI): "Yes" indicates H' index value smaller than 0.68 (less diversity) and "No" indicates H' index value larger than 0.68 (more diversity). The fifth row indicates the number of interdisciplinary authors (Interdisc_Author): "Yes" indicates fewer than four and "No" indicates four or more.



CONCLUSION AND DISCUSSION

Overall, our results showed that much of the research coming from interdisciplinary teams focused on coupled natural and human systems was still largely divided into separate natural and human components. There are more efforts to investigate incomplete linkages, leaving articles that incorporate two-way linkages to be far less common.

However, these analyses provide detailed results of how the attributes of interdisciplinary research teams are associated with the production of research articles that include two-way linkages between the human and natural systems. By incorporating results from four different analysis approaches (including Bayesian hierarchical logistic regression analysis, chi-squares tests, ANOSIM tests, and regression tree analysis), we are able to highlight which effects are the most robust. Bayesian hierarchical logistic regression analysis demonstrates that the random effects of individual grant awards do not have a strong effect on the likelihood that an article will include two-way linkages. Instead, the probability of producing two-way linkage articles more substantially depends on the analysis method utilized and the authors' and PIs' disciplinary backgrounds. Specifically, this analysis indicates that PIs from the computer science/math/engineering discipline, interdisciplinary authors, and a wider diversity of author disciplines each predict a greater likelihood that articles will include two-way linkages.

Chi-square tests and ANOSIM tests each consider one set of attributes while marginalizing across all other team and article attributes. Similar to the Bayesian hierarchical logistic regression analysis results, the chi-square tests also indicate that the authors from interdisciplinary disciplines are more associated with two-way linkage articles, whereas the authors from the physical science discipline are more likely to produce incomplete linkage articles. They also demonstrate that the analysis method plays an important role in producing two-way linkage articles.

Regression tree analysis provides another way of viewing the results. Again, analysis methods are an important indicator of articles with two-way linkages, with three specific analysis methods (conceptual/literature review, simulation model analysis, and mathematical analysis) utilized in almost all articles with two-way linkages. Once the method is determined, then authors' and PIs' disciplinary backgrounds start to play an additional role in an article's likelihood of including two-way linkages.

Researchers from biological/life sciences are the most common participants (as PIs and authors) in coupled natural and human system research. However, the presence of a biological/life scientist as a PI or team member does not increase the likelihood of producing articles that include the construction of two-way linkage models. If anything, there was some mixed evidence that authors from this discipline may produce more articles with incomplete linkages. Furthermore, authors from the physical sciences somewhat decreased the likelihood of producing articles that include two-way linkages. This result well reflects Boyack, Klavans, and Borner's science map (2005) that biological/life and physical sciences have lots of co-citations with other natural science fields including chemistry, physics, and soil, yet with much fewer co-citations with social science fields. Some major questions and research approaches in the physical sciences might have less intersections with a human system, which makes it difficult to develop two-way linkage models directly. There was also some mixed evidence that social science PIs may also reduce the likelihood of two-way linkage articles, perhaps because of similar difficulties connecting with the biological/life and physical sciences.

However, collaborating with individuals from across a wide range of disciplines can help. Indeed, there is partial evidence that the diversity of PIs' disciplines on a research team and the diversity of authors' disciplines on an article can each increase the likelihood of two-way linkages. As team leaders, PIs play a role in directing the research team to create collaborative research products (Stokols et al. 2006, Boone et al. 2020). Including PIs with different expertise in the natural and human systems can lead to research goals and study designs that more actively include elements of both systems. Similarly, when a specific article includes authors from a range of disciplines, it is less likely that the research will only focus on one system alone. Additionally, including researchers with interdisciplinary expertise may be particularly helpful in making connections from biological or physical science research in the natural system to the human system.

Indeed, our analyses consistently highlight the crucial role of researchers from interdisciplinary disciplines as authors of articles most likely to produce fully coupled two-way linkages. There may be several reasons for this. Team members' comprehension of the team goal and their past experience creating interdisciplinary products can determine the success in realizing two-way linkage models within an article (Pohl et al. 2015). It may be that these interdisciplinary members act as a bridge, identifying connections and effectively communicating these to other team members. Additionally, researchers housed in many traditional academic departments at universities may have few incentives to publish research with two-way linkages that go beyond the scope of their academic discipline. Academic systems for getting hired, preparing for tenure/promotion, and obtaining recognition may serve as barriers (National Academy of Sciences 2005). For example, what "counts" as a meaningful publication may be limited to only include disciplinary-specific work. Alternatively, researchers within interdisciplinary academic departments may receive greater support to conduct and publish across a broader range of research areas.

A major challenge in coupled natural and human systems research is to develop analytical methods that effectively capture and measure the interactions between human and natural systems across temporal, spatial, and organizational scales (Kramer et al. 2017). Certain methods are more likely to be used by researchers who can identify and incorporate two-way linkages in research articles. Concepts and methods are often rooted in specific disciplines that shape researchers' way of thinking about the world and way of conducting research. Even though researchers from different disciplines share a broad understanding of how research should be conducted, disciplinary differences in methodologies create barriers during interdisciplinary research efforts (Lach 2014). For example, statistics, the current most popular method in coupled natural-human model research, can easily be used to analyze incomplete linkages. However, these analyses generally do not contribute to two-way coupled models, perhaps because it is difficult to construct statistical models which capture non-linear effects driven by simultaneous interactions between natural and human systems. Our findings suggest that conceptual/literature review articles, simulation model analysis, and mathematical analysis can converge different disciplines to realize two-way linkages. Similarly, there was some evidence that PIs from the computer science/mathematical/engineering disciplines also contribute to more articles with two-way linkages, perhaps because of their expertise in conducting research using mathematical analyses or simulation models. Although a review article can be useful to develop a conceptual map among participating team members and describe important connections, a simulation model analysis is a critical way to tangibly connect different variables from the human and natural systems and to parametrize simultaneous effects among linkages. To advance the science of coupled human natural systems and related areas such as social-ecological sustainability in practice, research teams require more individuals equipped with the training to understand two-way linkage effects, the technical skills to collect and manage relevant datasets, and the expertise to run simulation models (Nastar et al. 2018).

However, the relatively low rate of research articles containing two-way linkages indicates that interdisciplinary teams are not the mere sum of members from different academic disciplines. An individual's disciplinary background and experience represent their way of training developed by a communal tradition of procedural and technical approaches to solve theoretical and practical problems (Toulmins 1972, Stein 2007). Even though PIs and team members from diverse single disciplines collaborate, if they are not inclined toward or capable of bridging intellectual understanding gaps or exploring and learning new methodological approaches, the team may likely have many separate research products rather than fully incorporated models (Miller et al. 2008). These contributions are still useful and important, but are more disciplinary specific, and they often do not actually couple natural and human systems to examine their interactions, feedbacks, and/or tipping points. Publications with incomplete linkages represented 86.4% of our sampled articles, which signifies the current gap of ability to create truly interdisciplinary products even though the grant award teams were selected through a competitive process.

One way to address the current challenges to developing integrative CNH research projects is through the further training and support of interdisciplinary researchers. We find that CNH teams that successfully produce research including two-way linkages are often composed of at least some team members affiliated with interdisciplinary academic departments. There are at least two pathways for an individual to gain necessary interdisciplinary background. One way is through receiving formal training in an interdisciplinary graduate program. There are now many graduate programs that include formal quantitative, biological, and social science training, such as many of the programs funded through the NSF Integrative Graduate Education and Research Traineeship grants (http://www.igert.org/). This includes programs in Environmental Economics, Big Data Social Science, or Socio-Technical Infrastructure for Electronic Transactions, to name a few. A second way would be for someone to develop interdisciplinary skills, vocabulary, and concepts by actively pursuing new experiences outside of their discipline through postdoctoral training, workshops, conferences, and/or research collaborations. We encourage both of these routes for individuals interested in building flexible thinking, gaining new analytical skills, for broadening their perspectives so as to incorporate new frameworks and methods with their existing knowledge.

One limitation of our analysis is that it focused on only research awards granted by the NSF CNH program, which in turn largely included U.S.-based research teams. Nevertheless, whereas this competitive research program was designed specifically to fund coupled natural and human system research without limiting the research to a specific field, this is a useful sample for investigating how the characteristics of teams relate to their research outcomes, and provides insights into the current challenges in conducting CNH research.

There has been much recognition of the importance of interdisciplinary teams to better understand complex issues that involve both natural and human processes. This has been highlighted not only by CNH researchers, but also by those in related areas such as social-ecological systems (Cote and Nightingale 2012), social-environmental systems (Engelen et al. 1995), or decision making under deep uncertainty (Marchau et al. 2019). Working to build effective teams that overcome the differences in disciplinary cultures, terminology, and methods to create shared conceptual understandings that can be tested and modeled will lead to greater progress in coupled natural and human systems research.

Responses to this article can be read online at:
https://www.ecologyandsociety.org/issues/responses.php/13228

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Data Availability:

The data/code that supports the findings of this study are openly available in Open Science Framework: https://osf.io/qfvjn/, reference number DOI 10.17605/OSF.IO/QFVJN.

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APPENDIX 1

Table A 1.1. Coding Criteria

PIs/ Authors' Discipline	Examples of Specific Department or Employer
1) Biological/Life Science	Agriculture, Biology, Botany, Conservation, Ecology, Environmental, Forestry, Forestry Service, Life Science, Limnology, Ornithology, Medicine, Natural Resources, Trout Station, Zoology
2) Social Science	Anthropology, Archaeology, Economics, Education, Law, Political Science, Public Policy, Social Science, Sociology
3) Physical Science	Astronomy, Chemistry, Energy, Geology, Hydrology, Meteorology, Oceanography, Physics, Soil & Water Science
4) Computer Science/ Math/Engineering	Architecture, Civil Engineering, Environmental Engineering, Civil & Environmental Engineering, Mechanical and Aerospace Engineering, Software engineering, Electrical and Computer Engineering, Computer Science, Information Science, Mathematics
5) Interdisciplinary	Business, "Development" departments, Geography, Finance, "Planning" departments, Resilience, Sustainability. Any department title that combines two disciplines from separate categories: (eg. Environmental Economics; Food, Agriculture & Development; Civil and Environmental Engineering & Earth Sciences; Biological and Ecological Engineering). Any Museums or Centers that may include members from natural sciences, social sciences, and humanities. Any individual who is affiliated with more than one academic department from different discipline categories.
6) Undefined	"Consulting" or people who are unaffiliated

Analysis Method	Criteria
1) Conceptual/Literature Review	Conceptual models, literature reviews, or case studies. These articles may descriptively explain relationships among different factors/concepts, review the literature on a specific concept or topic, or descriptively explain an individual/particular case study without using a quantitative analysis.
2) Statistics	Inferential analysis showing relationships among factors, such as Regression, ANOVA, Bayesian models, Meta-analysis, and Markov Chain Monte Carlo (MCMC).
3) Spatial Analysis	GIS with layers of maps. It may use statistical analysis to analyze results across spatial differences.
4) Mathematical Analysis	Mathematical formulas to explain conceptual relations, such as economic analysis or cost-benefit calculations.
5) Simulation Model Analysis	Explicitly simulate a study system including agent-based models, system dynamics models, temporal and spatial dynamics models, or interactive data language models.
6) Other	Meeting summary or observation report.

Degree of Coupling	**Coding**	**Criteria**
Incomplete Linkages	1.No linkages	If both one-way linkages are "No", the research presents no linkages.
	2. One-way linkages from natural to human systems	If any components from a natural system cause a change(s) of a component(s) in a human system, we code as "Yes". Otherwise, "No"
	2. One-way linkages from human to natural systems	If any components from a human system cause a change(s) of a component(s) in a natural system, we code as "Yes". Otherwise, "No"
Two-Way Linkages	3.Two-way linkages	If both one-way linkages are "Yes", the research presents a two-way linkage

Table A 1.2 Intercoder reliability by coding category

Subject	No. of testing sample	No. of criteria to match	% Agreement	Cohen's Kappa
Authors' Discipline	220 authors (from 36 articles)	6	82%	0.724
Analysis Method	36 articles	5	97%	0.958
No Linkages	36 articles	2	100%	1
One-Way Linkages Natural-->Human	36 articles	2	94%	0.769
One-Way Linkages Human-->Natural	36 articles	2	100%	1
Two-Way Linkages	36 articles	2	94%	0.769

Supplemental Analysis:

As an additional exercise, we also conducted the same chi-square and ANOSIM tests examining how each team or article attribute related to degree of coupling when all three linkage types were examined. Again, PIs specific disciplines were not associated with degree of coupling ($\chi 2 = 5.26$, df = 8, $p = 0.73$), and no significant difference between sampled chi-squares and the chi-square of the observed data ($p = 0.74$). The diversity of PI's academic disciplines did not significantly differ for articles with two-way linkages (*H'* = 1.21), one-way linkages (*H'* = 0.65), or no linkages (*H'* = 1.04), ANOSIM R = 0.00, $p = 0.44$.

However, we did find a significant association between authors' specific discipline and the degree of coupling ($\chi^2 = 57.16$, $df = 8$, $p < .001$) as well as a significant difference between the sampled chi-squares and the chi-square of the observed data ($p < .001$, see Table A 1.3). The significant associations come from all disciplines except authors from computer science/math/engineering. Physical science authors were more likely to be involved in no-linkage articles (Residuals = 4.30, $p < .001$) and less likely to be involved in two-way linkage articles (Residuals = -3.61, $p = .005$). Biological/life authors were less likely to be involved in two-way linkage articles (Residuals = -3.37, $p = .01$). In contrast, interdisciplinary authors were less likely to be involved in no-linkage articles (Residuals = -4.18, $p < .001$) and more likely to be involved in two-way linkage articles (Residuals = 4.68, $p < .001$). Social science authors were less likely to be involved in no-way linkage articles with a marginal extent (Residuals= -2.77, $p = .08$). Authors from computer science/math/engineering did not lead to significant differences in degree of coupling ($p = .86$). The diversity of authors' academic disciplines did not significantly differ for articles with two-way linkages (*H'* = 1.38), one-way linkages (*H'* = 1.19), or no linkages (*H'* =1.24), ANOSIM R = 0.04, $p = .24$.

Table A 1.3. Observed values and expected values demonstrating the relationship between authors' disciplines and degree of coupling in the articles

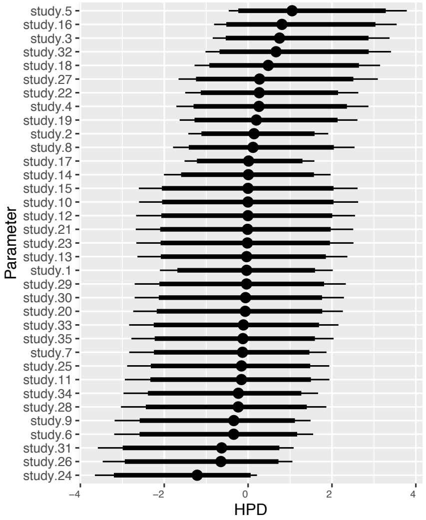
	Biological/Life		**Social Science**		**Physical Science**		**Computer Science/ Math/ Engineering**		**Interdisciplinary**		**Total**
	Obs.	**Exp.**	**Obs.**	**Exp.**	**Obs.**	**Exp.**	**Obs.**	**Exp.**	**Obs.**	**Exp.**	
No Linkages	382 (27.3%)	365.5 (26.1%)	42 (3.0%)	55.3 (4.0%)	102 (7.3%)	77.8 (5.6%)	57 (4.1%)	49.3 (3.5%)	183 (13.1%)	218.1 (15.6%)	766 (54.8%)
One-Way Linkages	206 (14.7%)	199.9 (14.3%)	35 (2.5%)	30.3 (2.2%)	33 (2.4%)	42.6 (3.0%)	19 (1.4%)	27.0 (1.9%)	126 (9.0%)	119.3 (8.5%)	419 (30.0%)
Two-Way Linkages	79 (5.7%)	101.6 (7.3%)	24 (1.7%)	15.4 (1.1%)	7 (0.5%)	21.6 (1.5%)	14 (1.0%)	13.7 (1.0%)	89 (6.4%)	60.6 (4.3%)	213 (15.2%)
Total	667 (47.7%)		101 (7.2%)		134 (10.2%)		90 (6.4%)		398 (28.5%)		1398 (100%)

We also found a significant association between analysis method and the degree of coupling ($\chi^2 = 35.46$, $df = 10$, $p < .001$) as well as a significant difference between the sampled chi-squares and the chi-square of the observed data ($p < .001$, see Table A 1.4). Articles that used statistics were less likely to include two-way linkages (Residuals = -3.73, $p = .002$) and more likely to include no linkage (Residuals = 2.88, $p = .07$). Alternately, conceptual/literature review articles were more likely to include two-way linkages (Residuals = 3.77, p =.003). The other analysis methods (spatial analysis, mathematical analysis, and simulation model analysis, and "other") did not lead to significant differences in degree of coupling $p > .30$.

Table A 1.4. Observed values and expected values demonstrating the relationship between analysis method and detailed degree of coupling in the articles

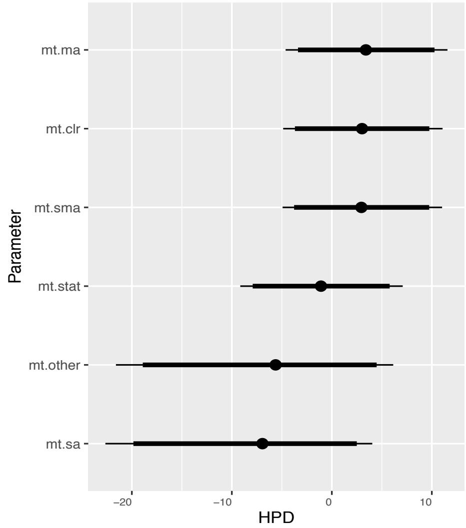
	Conceptual/ Literature review		**Statistics**		**Spatial analysis**		**Mathematical analysis**		**Simulation model analysis**		**Others**		**Total**
	Obs.	**Exp.**	**Obs.**	**Exp.**	**Obs.**	**Exp.**	**Obs.**	**Exp**	**Obs.**	**Exp.**	**Obs.**	**Exp.**	
No linkage	26 (10.8%)	26.7 (11.1%)	51 (21.2%)	40.3 (16.7%)	8 (3.3%)	10.3 (4.3%)	4 (1.7%)	5.2 (2.1%)	23 (9.5%)	30.0 (12.5%)	1 (0.2%)	0.47 (0.2%)	113 (46.9%)
One-way	15 (6.2%)	22.7 (9.4%)	33 (13.7%)	34.3 (14.2%)	14 (5.8%)	8.8 (3.6%)	4 (1.7%)	4.4 (1.8%)	30 (12.4%)	25.5 (10.6%)	0 (0 %)	0.40 (0.2%)	96 (39.8%)
Two-way	16 (6.6%)	7.6 (3.1%)	2 (0.8%)	11.5 (4.7%)	0 (0%)	2.9 (1.2%)	3 (1.2%)	1.5 (0.6%)	11 (4.6%)	8.5 (3.5%)	0 (0%)	0.13 (0.1%)	32 (13.3%)
Total	57 (23.7%)		86 (35.8%)		22 (9.1%)		11 (4.6%)		64 (26.6%)		1 (0.4%)		241 (100%)

Figure A 1.1. Posterior distributions of odds ratios of each grant award's likelihood of producing articles that include two-way linkages



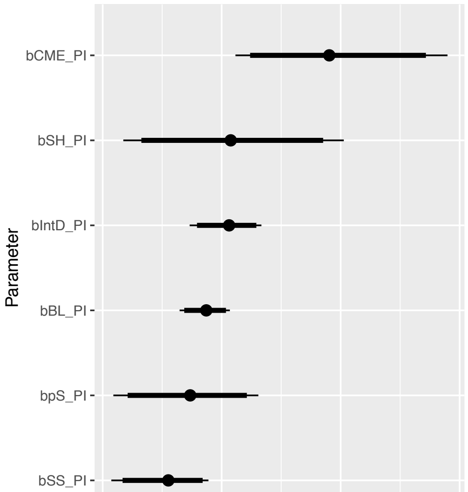
Note: Caterpillar plots of the output from the Bayesian hierarchical logistic regression analysis (including 90% Bayesian credible intervals). The figure displays the random effects of each grant on its likelihood of producing articles that include two-way linkages. The y-axis indicates grant numbers and the x-axis indicates highest posterior density (HPD) interval for each grant award.

Figure A 1.2. Posterior distributions of odds ratios of analysis method and likelihood of articles including two-way linkages



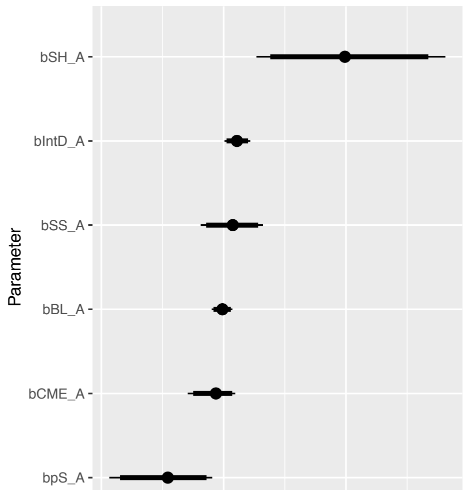
Note: Caterpillar plots of the output from the Bayesian hierarchical logistic regression analysis (including 90% Bayesian credible intervals). The figure displays the effects of each analysis method on likelihood of two-way linkages. The y-axis indicates analysis method categories: mt.ma = mathematic analysis, mt.clr = conceptual/literarture review, mt.sma = simulation model analysis, mt.stat = statisical analysis, mt.other = other, mt.sa=spatial analysis. The x-axis indicates highest posterior density (HPD) interval for each analysis method category.

Figure A 1.3. Posterior distributions of odds ratios of PIs' disciplines and likelihood of articles including two-way linkages



Note: Caterpillar plots of the output from the Bayesian hierarchical logistic regression analysis (including 90% Bayesian credible intervals). The figure displays the effects of each PI academic discipline and diversity of PI's disciplines on likelihood of two-way linkages. The y-axis indicates PI's disciplines: bCME_PI = computer science/math/engineering, bSH_PI = Shannon diversity index for PIs, bIntD_PI = interdisciplinary, bBL_PI = biological/life science , bpS_PI = physical science, bSS_PI = social science. The x-axis indicates highest posterior density (HPD) interval for each PI factor.

Figure A 1.4. Posterior distributions of odds ratios of authors' disciplines and likelihood of articles including two-way linkages



Note: Caterpillar plots of the output from the Bayesian hierarchical logistic regression analysis (including 90% Bayesian credible intervals). The figure displays the effects of each author academic discipline and diversity of authors' disciplines on likelihood of two-way linkages. The y-axis indicates authors' disciplines: bCME_A = computer science/math/engineering, bSH_A = Shannon diversity index for authors, bIntD_A = interdisciplinary, bBL_A = biological/life science, bpS_A = physical science, bSS_author = social science. The x-axis indicates highest posterior density (HPD) interval for each author factor.