Ecological Synthesis and Its Role in Advancing Knowledge

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Synthesis has become ubiquitous in ecology. Despite its widespread application to a broad range of research topics, it remains unclear how synthesis has affected the discipline. Using a case study of publications (n = 2304) from the National Center for Ecological Analysis and Synthesis compared with papers with similar keywords from the Web of Science (n = 320,000), we address several questions about the comparative impact of synthesis, the role of synthesis in driving key research themes, and whether synthesis is focused on different topics than is the broader ecological literature. We found much higher citation rates for synthesis papers overall (fivefold more) and within eleven key topic themes (e.g., species richness, biodiversity, climate change, global change). Synthesis papers often played key roles in driving, redirecting, or resolving core questions and exhibited much greater cross-theme connectivity. Together, these results indicate that synthesis in science has played a crucial role in accelerating and advancing ecological knowledge.

Keywords: synthesis, environmental science, impact assessment, research trends

Over the last 25 years, synthesis has become an increasingly common and impactful approach for conducting ecological research. Indeed, more than 20 ecological synthesis centers have been created around the world (Baron et al. 2017), with a consistent goal to address multidisciplinary analysis of complex ecological and environmental problems through synthesis. At the core of the approach is the assumption that synthesis plays a key role in advancing basic science by generating novel insights and solutions to old problems, better organizing ecological information for decision-makers concerned with pressing societal issues and making effective use of existing data (Hackett et al. 2008). There are ample anecdotal examples of how ecological synthesis has accelerated advances in ecological knowledge by integrating evidence and identifying important knowledge gaps.

In ecology, synthesis is the act of combining data, theories, and tools from ecology and other disciplines (Carpenter et al. 2009). Synthesis takes the form of meta-analyses, reviews, and the integration of theory and conceptual models, as well as spatial data (e.g., maps) and other data aggregations, all of which are implemented to examine foundational theory or relatively larger-scale problems or issues through time or across space. As human-induced change intensifies, synthesis also offers a rapid and efficient way to provide relevant insight into complexities that can ultimately lead to a shared understanding of the issues and novel solutions.

The maturation of synthesis as a mode of inquiry and understanding provides the opportunity to assess its long-term role and impact on the nature and cadence of scientific discovery. At a general level, the impact of synthesis on the practice of ecology is evident through a large number of highly cited publications, investment in infrastructure for synthesis centers around the world, and the adoption of synthesis as a key component of modern scientific inquiry. Beyond this general level, can we identify whether synthesis is uniquely impactful and, if so, in which ways? Given the urgency to understand the patterns and processes underlying pressing global environmental problems, there is additional value in taking stock of the impact of synthesis research to understand its potential for addressing these urgent needs moving forward.

In the present article, we quantify the impact of synthesis on the fields of ecology and conservation science. Specifically, we assess the often-cited assumption that synthesis has increased the pace of advancement of scientific knowledge generation (Wyborn et al. 2018, Leahey et al. 2019). To address this broad objective, we answer three specific questions: How does the impact of synthesis in ecological science compare with other modes of research in the ecological literature? What roles has synthesis played in driving, redirecting, or resolving major lines of inquiry in the field of

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Box 1. Mining the case study.

The NCEAS maintains a database of all publications produced from projects it hosts. In total, 5989 papers were published between January 1997 (the time of the first NCEAS publication) and December 2018. We did not include papers from 2019 because they would not have accumulated sufficient citations to determine their influence in ecology. We then excluded any papers led by postdoctoral fellows, sabbatical fellows, or the SEEK (ecoinformatics) project, because these are often not synthesis science publications (because they were done before but published while in residence at the NCEAS), leaving 2304 papers. We used this corpus of literature (hereafter called *synthesis papers*) to extract a set of keywords from the Web of Science using the enhanced keyword feature (drawing on keywords additionally from each paper's cited references or bibliography).

Next, we used the most common 10 keywords from this list, supplemented with additional keywords from Carmel and colleagues (2013), who looked at trends in ecological research over the previous 30 years, as well as our input on any missing terms (see the supplemental material for the keyword string), to search the entire Web of Science database for all matching papers between 1 January 1997 and 31 December 2018. Our search string likely missed some key papers, but if so the omission is unlikely to change our overall results given the sample size.

The query was structured to search for high-level concepts (e.g., ecology, biodiversity, climate change, biogeography) and then use subdiscipline-specific concepts within those results to remove papers from other disciplines that either mention the high-level concepts in passing in the abstract or, as in the business world's use of the term *ecosystem*, assign a term associated with a high-level concept with a new meaning and apply it in a different domain. The search produced 318,375 papers (of the roughly 900,000 ecology papers from this time period).

To produce a comparable set of papers to explore the relative influence and impact of synthesis papers on core ecological ideas, we filtered the database of synthesis papers that used the top keywords in their most appropriate subdiscipline (see supplemental table S1), using the same keyword matching algorithm as above. Of the 2304 synthesis papers, 1248 (54%) matched. To control for the fact that NCEAS working group participants may already be highly cited authors independent of synthesis, we analyzed only the subset of papers with a citation rate (number per year) greater than the median citation rate of all 2304 synthesis publications (5.15 per year). This filter removes the many papers with zero citations (8.37% of control papers; 0 synthesis papers) or just one (an additional 6.82% and 0.72%, respectively) over the 22-year period. Combining the top keyword filter with the median citation rate filter resulted in a data set of 54,577 of the 318,375 control papers from Web of Science (17.1%) and 723 of the 2304 synthesis papers (31.4%). Finally, we manually checked all 723 synthesis papers and removed any that did not meet the definition of synthesis—that is, the combination of data, theories, or tools ($n = 65$, leaving 658 papers). We then randomly sampled five sets of 100 papers from the control set to determine the expected number of synthesis papers in that set (see the supplementary material) and, from this analysis, estimated 17.6% of the 54,577 control papers are synthesis.

ecology, and what can we learn from the specific papers that played these key roles? And has synthesis been focused on a different set of topics than other types of ecological research? To address these questions, we use 25 years of data from the longest running ecological synthesis center, the National Center for Ecological Analysis and Synthesis (NCEAS), where many publications are synthesis products. Therefore, data on publications stemming from the NCEAS provide a unique long-term case study to track the genesis, spread, and impact of ideas born of synthesis research.

Quantifying the impact of synthesis

As a case study, we focused on publications emerging from synthesis work supported by the NCEAS. The NCEAS is a salient case study for three reasons. First, the total ecological literature from the past 25 years is extremely large, making it difficult to filter out the complete or even a representative set of synthesis papers ($n > 900{,}000$ publications in that time span). Using papers produced from a synthesis center provides an efficient way to solve this identification and selection challenge. Second, the NCEAS was an early incubator of synthesis research in ecology, providing the longest-running set of research publications from a synthesis center. Finally, the NCEAS has brought together researchers from all over the world and can therefore function as an indicator of synthesis science within and beyond the United States. Our approach for mining these data is detailed in box 1.

Using this case study of synthesis papers, we addressed our three core questions as follows (further details are available in the supplemental material). To evaluate whether synthesis papers had a larger impact within a topic theme than would be expected on average (question 1), we compared the proportion of highly cited synthesis papers with the proportion of highly cited papers from control publications for each topic theme. To determine whether and how synthesis papers within each theme helped drive, redirect, or resolve key research themes (question 2), we identified key synthesis papers by repeating the analysis above, comparing the observed total citation rate for synthesis papers each year within each theme with 1000 random samples of size n, where n is the number of synthesis papers in that group (supplemental table S5). We then qualitatively evaluated the role of key papers associated with the timing of citation

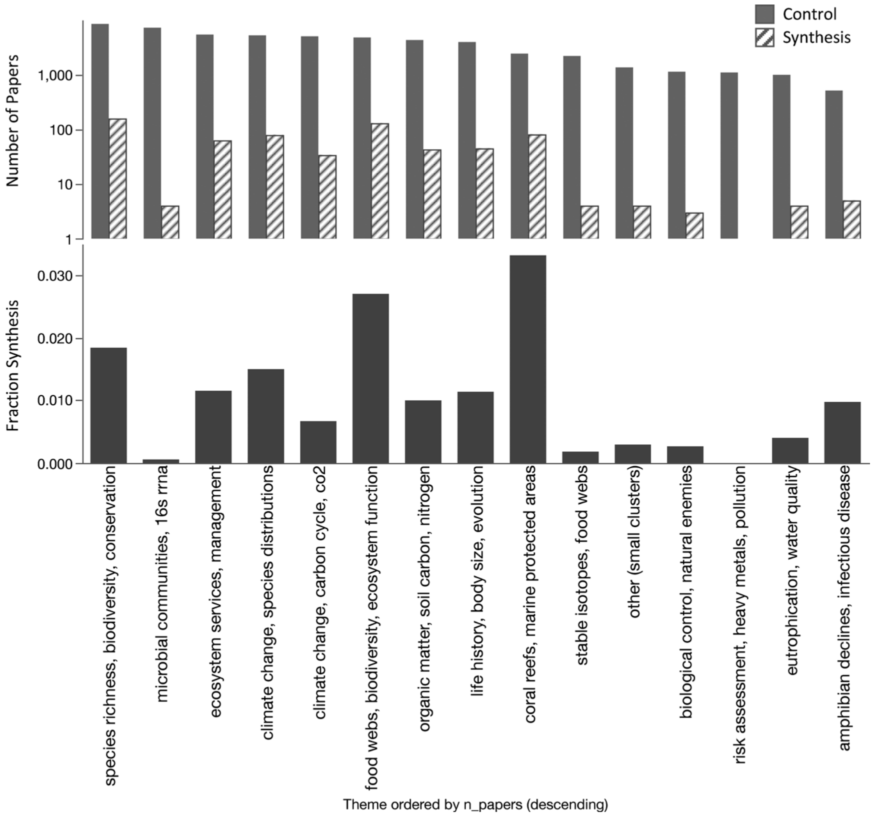

Figure 1. The number of synthesis papers in each theme relative to the total number of publications within the highly cited corpus. Themes represent sets of keywords that define clusters of similar papers. Theme labels are not exclusive; for example, papers focused on biodiversity can fall into themes other than biodiversity.

peaks in initiating, driving, or resolving a research trajectory. We achieved this by reading the key papers to determine their importance and then examined forward citations to determine their role in the research trajectory, as well as the breadth and types of research areas affected by the paper. Finally, we assessed the extent to which the synthesis papers fell closely within a given topic theme or spanned more than one theme (termed an *edge* position), using three metrics (cluster diversity, bridging, and archetype scores) and whether this position differed from those of papers in the control corpus (question 3).

The impact of synthesis relative to that of other research modes. Across the entire set of approximately 320,000 control publications, the full set of 2300 synthesis publications were, on average, cited five times more often than control papers. Furthermore, the 65 nonsynthesis papers removed from the synthesis data set (box 1) were cited significantly less often than the synthesis papers from this set (*t*-test, $t = 2.7$, $p < .01$; see the supplemental material). Within each theme, the synthesis papers represented 1.1% of the total publications on average (range = 0%–2.3%; figure 1). These percentages are notable and do not include other synthesis papers in the control corpus. The highest relative citation value was for papers in the species richness, biodiversity theme (2.3%).

Within the subset of papers that exceeded the median citation rate (see box 1), synthesis papers consistently had a higher—and, in several cases, much higher (i.e., three times higher)—fraction of the total citations than would be expected by the fraction of papers within each theme (figure 2). This is likely an underestimate of the impact of synthesis, because synthesis papers are also present in the control group (estimated at 17.6%; see box 1). These proportions of synthesis papers were significantly higher for eight themes (figure 3), particularly those dealing with current environmental crises (climate change, ecosystem services, food webs, or species richness and biodiversity) and especially so for the ecosystem services theme.

Synthesis papers were significantly more likely to be connector papers (box 2), spanning more than one theme cluster (figure 4). Connector papers connect multiple clusters and so have high cluster diversity and cluster bridging, where cluster diversity measures the diversity of the clusters with which a paper is connected, and cluster bridging measures both the diversity and connectedness across clusters. Indeed, the control papers were essentially entirely within clusters (diversity and bridging scores at 0), whereas the synthesis papers had average diversity values close to 0.4 and bridging values close to 0.3, indicating they are 0.4 and 0.3 standard deviations, respectively, greater than the average score of papers in that cluster.

The types of impact of synthesis on ecological research trends. The timing of impact of synthesis publications examined in the present article, relative to the control literature, provides insight into the potential role of synthesis in initiating, driving, or potentially resolving research themes (figure 3). We explored this influence by looking at the timing of publication within the trajectory of a topic theme for very high-impact (high citation rate) papers. For instance, in the food webs or biodiversity themes, the synthesis papers had early high-impact contributions in the late 1990s, associated with the rise of the biodiversity and ecosystem function debates, particularly the explicit incorporation of biodiversity into these discussions (e.g., Palmer et al. 1997, Loreau et al. 2001). A second peak in the prevalence of the biodiversity theme in the literature occurred in the years surrounding 2010 and

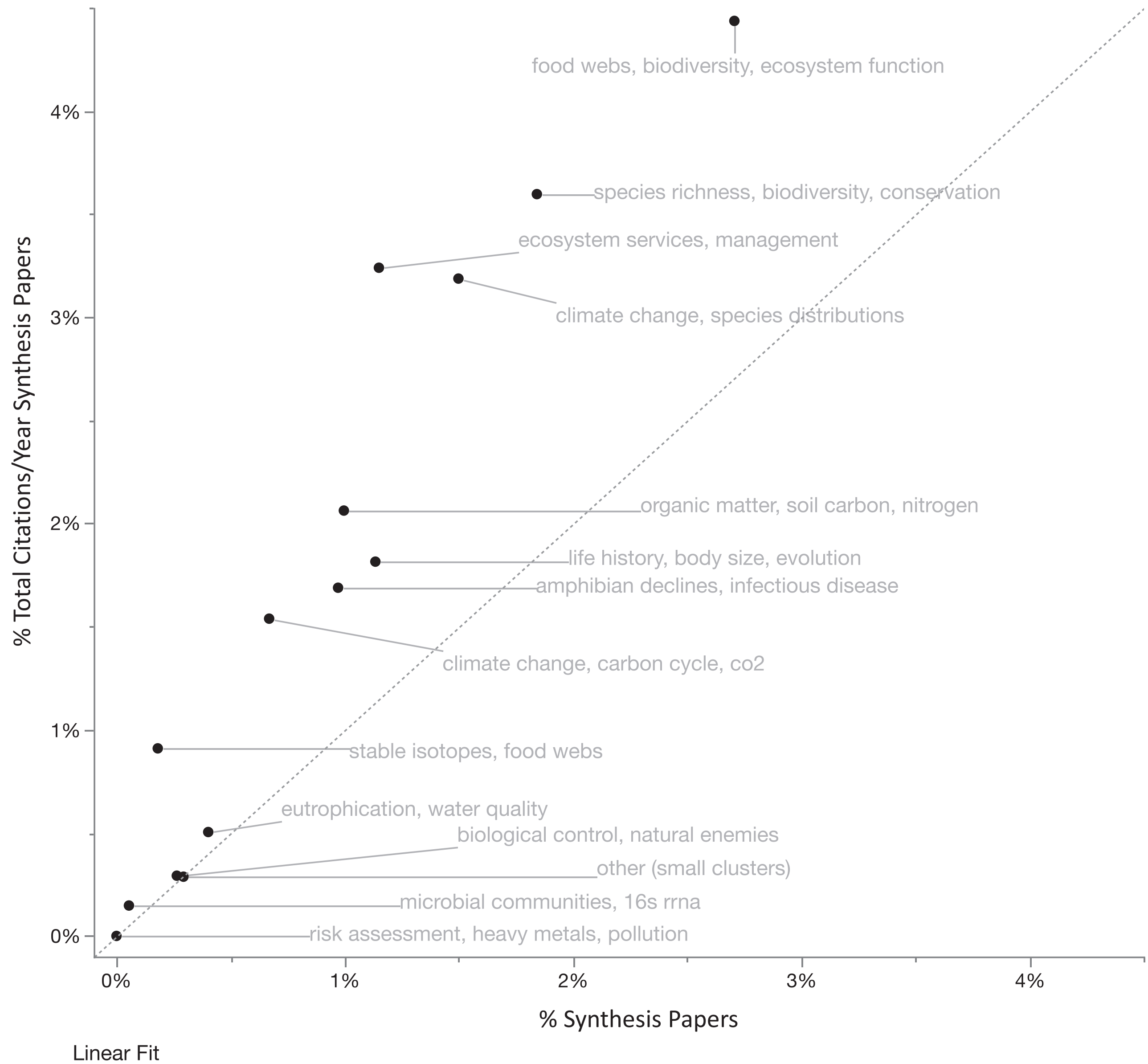

Figure 2. The relative impact of synthesis on non-synthesis papers. The percentage of papers above the median citation rate versus percentage of total citations for synthesis papers within a theme. The points above the line indicate a greater than expected citation impact. For a list of the individual top cited synthesis papers in each theme, see supplemental table S4.

was associated with attempts to resolve that debate (e.g., Cavender-Bares et al. 2009, Cardinale et al. 2011, Cadotte et al. 2012).

Pioneering synthesis work is evident in several other themes as well. The microbial communities theme's peak in 2006 was from pioneering work (Green and Bohannan 2006, Martiny et al. 2006) that preceded an exponential growth phase of microbial ecology research and is related to the rise in gut microbiome research. The life history theme had two early influential papers, one by Hedges and colleagues (1999) on meta-analysis and one by Gillooly and colleagues (2001) on metabolic scaling laws. The stable isotopes, food webs theme had a key early paper by Post (2002) on the use of stable isotopes to estimate species' trophic position. Finally, the ecosystem services theme included a very early influential synthesis paper in which the authors attempted to estimate the global economic value of ecosystem services (Costanza et al. 1996). This interdisciplinary synthesis paper brought economics and ecology together with conservation and helped define the field devoted to the study of ecosystem services. This work also motivated numerous synthesis publications seeking to improve on or correct the seminal work and resulted in significant contributions from these publications throughout the time period. For the management side of this theme, the interdisciplinary synthesis work of Jackson and colleagues (2001) helped catapult historical ecology to

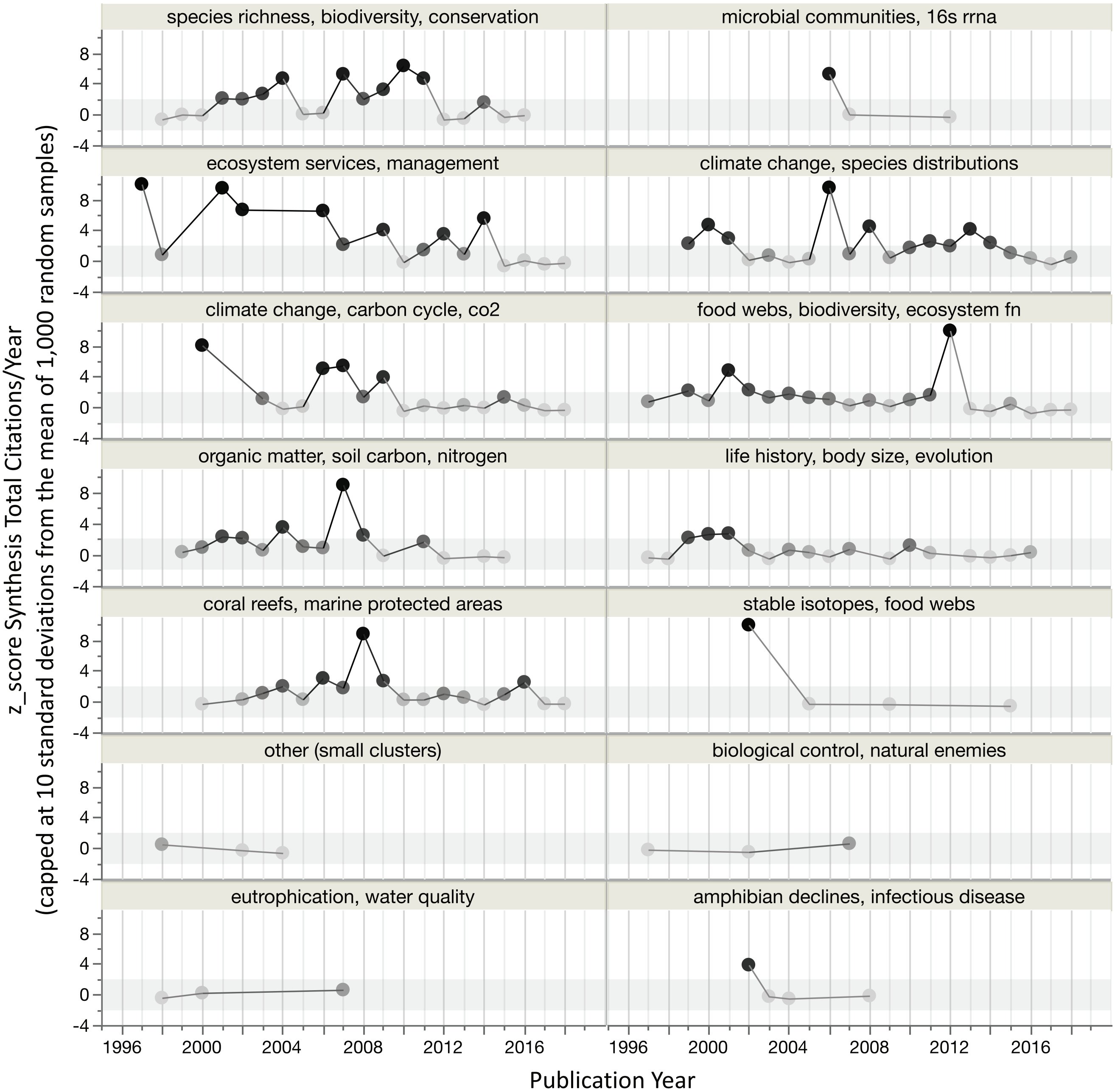

Figure 3. The timing and influence of synthesis papers within key topical themes. Each bar shows the z-scores for synthesis papers per year, per theme. The gray band is the region in which citation rates for synthesis papers were within 2 standard deviations of the mean of 1000 random samples of the same number of control papers. The z-score was capped at 5 standard deviations from the mean. Note that the theme* ecological risk, risk assessment *is not shown because there were no synthesis papers present. For a list of the individual top cited synthesis papers in each theme and year, see supplemental table S5.

the mainstream and draw attention to the issue of shifting baselines in ecological reference points.

Both themes related to climate change—climate change, species distributions and climate change, carbon cycle, carbon dioxide—demonstrated a somewhat different pattern of sustained but more punctuated impact of synthesis papers. For the climate change, species distribution theme, early work by Easterling and colleagues (2000) helped focus climate change science on the role of climate extremes. Later work synthesized global data to highlight accelerating loss of key habitats (Waycott et al. 2009), among many other key synthesis papers in these themes.

For the climate change, carbon cycle, carbon dioxide theme, early work by Sala and colleagues (2000) forecast outcomes

Box 2. Visualizing a synthesis network.

To identify broad themes in ecological research, we clustered documents within the control set of approximately 54,000 papers with similar combinations of keywords. Each paper's keyword set is enhanced by splitting its abstract into 1–3 word *ngrams* (i.e., collections of n number of words, or grams) and then adding any ngrams found in the global set of keywords but not in the paper's keywords. We extracted these keywords for both the synthesis papers and the entire control corpus to allow comparison of the role of synthesis versus other research modes in ecological thought (top keywords in the synthesis versus control group).

To visualize the scope of research in the set of selected synthesis papers, a document network was then built by linking papers on the basis of the similarity of their keywords (figure 5a). The network is clustered (using the Louvain algorithm) and named by selecting the most common keywords of the papers in the cluster (Lu et al. 2014). The clustering algorithm builds the network by first using a greedy process to create clusters that maximize keyword similarities within clusters, then using the network of these clusters (and new nodes) to refine (i.e., weight) the distance and connections among them. A theme's name (e.g., *biodiversity*) does not imply that it includes every paper with the same keyword (e.g., *biodiversity*). For example, a paper with biodiversity as a keyword could be in the microbial communities theme if it co-occurred with other keywords characteristic of that theme (figure 5b). The resulting network also allows identification of whether a paper falls tightly within a theme cluster (i.e., it is very similar to other papers in the cluster on the basis of keywords) or sits more at the edge between clusters, sharing similarity to multiple clusters (see box 1).

The clustering process produced 13 major themes with more than 500 papers and a fourteenth miscellaneous group theme for topics that had fewer than 500 papers (see supplemental table S2 for a theme list and the number of papers). Lists of the top keywords in each theme are provided in supplemental table S3 for reference.

for global biodiversity under climate change, whereas later work assessed global implications of nutrient limitations for primary producers (Elser et al. 2007) and integrating freshwater and terrestrial global carbon cycles (Cole et al. 2007). These mid–time-series papers are clear examples of synthesis papers that redirected thinking for entire disciplines. For example, Elser and colleagues (2007) synthesized experiments across marine, terrestrial, and freshwater ecosystems, and the results overturned a long-held assumption and nitrogen and phosphorus limitation in different systems by demonstrating generality in controls on plant biomass production (carbon uptake). Similarly, Cole and colleagues (2007) used synthesis of data on carbon fluxes in freshwater systems to demonstrate the surprisingly important role of lakes in regional carbon balances, in spite of their relatively small area.

Other themes had key papers during the middle of the time period. The climate change or species distribution theme's peak in 2006 is attributed to a key paper on methodological improvements to species distribution models Elith and colleagues (2006), and the life history theme's peak in 2006 is due to an influential synthesis paper on seasonality in infectious diseases (Altizer et al. 2006) that bridged subdisciplines and redirected thinking about the role of climatic change in infectious disease.

Similarity (or dissimilarity) of synthesis research topics. Most common keywords in the synthesis papers were notably similar to those in the control papers, (e.g., 6 of the top 10 keywords were the same) but had key differences as well (see supplemental table S4). In particular, *species diversity*, *food webs*, and *population dynamics* were top keywords for the synthesis publications but not the control corpus. Of the top 100 keywords in each set, only 40% were the same, and these had very different rank order positions. Curiously, marine reserves, community assembly, dispersal, competition, body size, and ecosystem-based management were proportionally more common in synthesis papers than the control papers.

Learning from the past while looking forward

Our analysis of ecological synthesis papers demonstrates that, although synthesis papers generally address similar topics as the rest of the ecological research field, they often had greater impact on research fields and could play unique roles in ecological subdisciplines by starting, changing the direction of, or concluding an area of inquiry. Therefore, synthesis—the combined analysis of dispersed data, theories, and tools—can shed light on old questions and clarify crucial next steps for data collection, as well as the application of new knowledge, providing a powerful tool to advance ecological understanding in ways that respond to the need to solve urgent environmental problems.

The synthesis papers analyzed in the present article consistently had a significantly greater impact on research fields than did the papers from the control group and initiated and sustained many key research themes in ecology. Many of the most influential synthesis papers in ecology in the last 25 years (measured by citation rates) have come from these publications, and their impact compared with that of nonsynthesis papers is likely underestimated, because some of the control papers are also syntheses. Importantly, these higher citation rates are not a result of synthesis papers having more authors (and therefore potentially increasing self-citation rates; see supplemental figure S1); the number of authors per paper was essentially the same between the two groups of papers, and in fact, the papers with very large numbers of coauthors were more likely to be in the control group of publications.

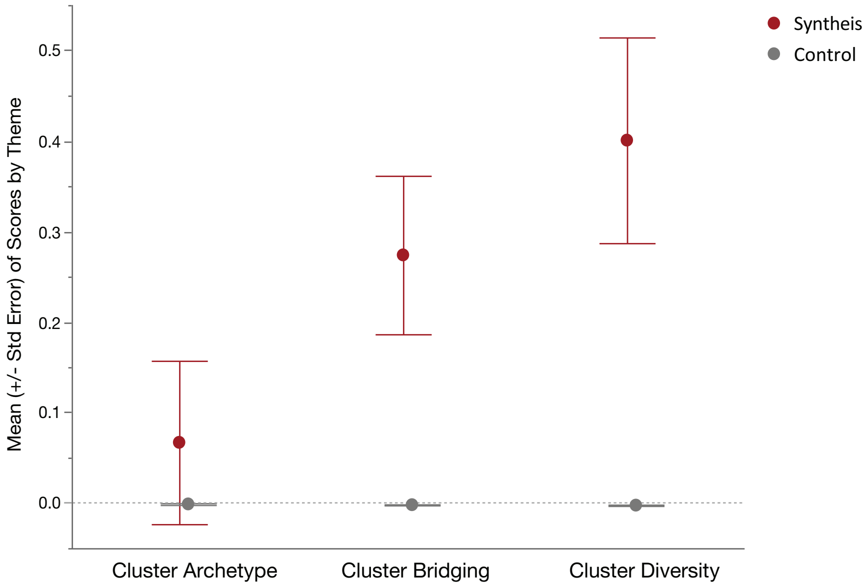

Figure 4. Cross-theme connections of synthesis papers relative to nonsynthesis papers. Cluster archetype measures connectedness within the paper's cluster, cluster diversity measures the diversity of the clusters with which a paper is connected, and cluster bridging measures both the diversity and connectedness across clusters.

The selected synthesis papers generally spanned multiple topics (i.e., were connector papers), whereas the control group of papers generally fit within a single topic cluster, highlighting the role that synthesis plays in bringing diverse ideas, data, and disciplines or subdisciplines to bear on crucial research questions. Relatedly, the synthesis papers had a greater diversity of keywords associated with them, and these keywords tended to be different from those of other papers. Our analysis points to the importance of synthesis in bridging areas to facilitate important knowledge advances. The papers in this case study include both interdisciplinary syntheses, bridging traditionally separate academic disciplines (e.g., economics and ecology, as with Costanza et al. 1996), and syntheses that bridge other axes that are not traditionally convolved (e.g., direct comparisons of marine, terrestrial, and freshwater responses, as with Elser et al. 2007).

Beyond citation metrics. There are, of course, many ways to measure impact and influence within a discipline beyond simple citation metrics. Some of these measures relate to efficiency—for example, the rate at which discoveries are made or the cost or the return on investment for a given research product. Others relate to the types of questions that can be addressed—for example, the geographic scale or transdisciplinarity of research. Still others relate to building community—for example, assessing diversity of participation or the size and stability of research networks. The focus of this analysis on citation metrics is not intended to diminish the importance of these other forms of research impact. Many of these measures are difficult to assess because of inaccessible or very difficult to acquire data (e.g., research return on investment, networks formed) and are therefore beyond the scope of this study.

Impact and influence can be measured in many additional ways beyond effects on the discipline, most notably with respect to how much any given research output leads to changes in policy, management, or human behavior. Indeed, many of the synthesis papers included in this assessment have had important applied outcomes. For example, Jambeck and colleagues (2015) catalyzed awareness of plastic pollution as a key threat to ocean condition in a way that substantially raised public awareness and subsequently helped shape management and conservation activities, and Worm and colleagues (2006) showed the role of diversity in stabilizing global fisheries catch, with the corollary influential and controversial result concerning the risk of global fisheries collapse. In many of these cases, the authors worked closely with science communication groups to amplify research messages and connect with policymakers to help shape management (Branch et al. 2016)

The future of synthesis in ecology. Synthesis is likely to play an increasingly important role in ecology, given its focus on integrating data and knowledge to advance understanding and to increase its applicability to address practical problems (Pickett et al. 2007, Carpenter et al. 2009, Baron et al. 2017). The growing availability of extremely large (e.g., high-resolution satellite data, such as Sentinel-2, MODIS, and AVHRR) and widely replicated (e.g., NEON) ecological data sets; greater access to traditional archived data, such as museum specimens through digital technology; exponential growth in novel data from social media and citizen science; and the computational tools with which to extract patterns and responses is presenting new opportunities for synthesis, in turn increasing the scale, speed, and scope of the questions that can be addressed. Work that, in the past, took hundreds if not thousands of hours to discover, clean, compile, standardize, and analyze data that were scattered across diverse and globally distributed study sites can now be done in a few days by a single well-trained researcher. The changes in data availability over the past 25 years and the data science tools to use those data are nothing short of profound; the next 25 years are likely to prove equally transformative for synthesis in science.

Furthermore, heightened awareness of the urgency of many current environmental problems is making the need for synthesis even greater. The many disciplines needed to understand and address modern environmental problems additionally create opportunity and need for synthesis.

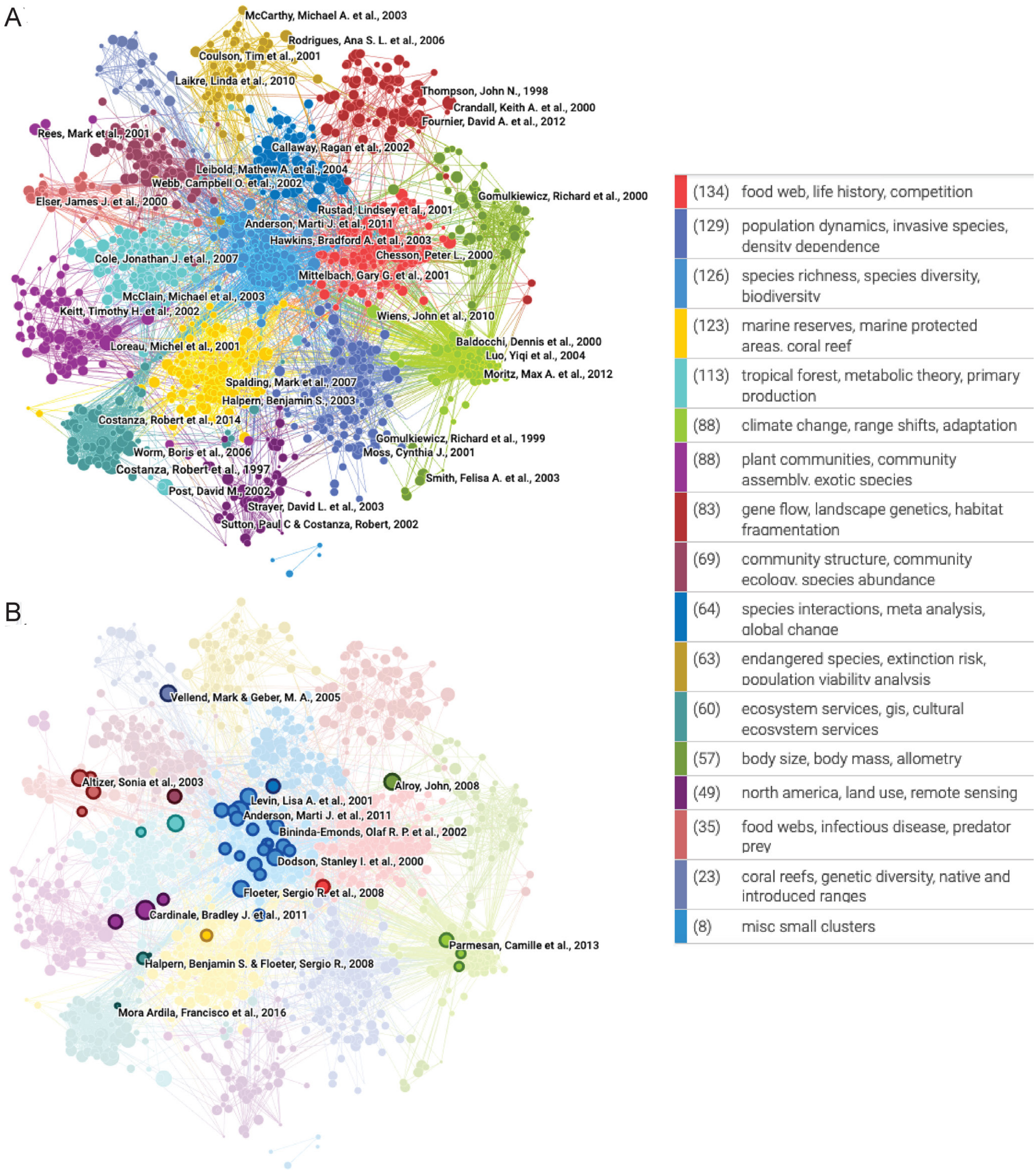

Figure 5. The network of synthesis papers from the NCEAS, with each node a paper and links connecting papers with shared keywords. (a) The 1312 synthesis papers with at least one keyword, with keyword thematic clusters color coded. The theme cluster labels are based only on this set of papers, not the entire control set, and so differ from those reported in the papers. (b) Some of the papers containing the keyword biodiversity highlighted, showing how different keyword thematic clusters can contain the same keyword. Legend shows top keywords for each cluster, and the number of papers in the cluster. The full database can be explored at https://openmappr.com/play/NCEAS_Keyword_Network.

Indeed, the push toward convergent science that is increasingly transdisciplinary is ultimately going to push ecological science toward synthesis approaches.

Synthesis does not happen spontaneously. It requires infrastructure—the space and time for researchers to work collaboratively to think, compile data, conduct analyses, interpret results, and write (Baron et al. 2017). Ecological synthesis centers have been created in response to this need and in recognition of the large quantity but dispersed nature of ecological data to be synthesized. These centers often evolve into scientific organizations that aim to promote and support research that integrates diverse theories, methods, and data across spatial or temporal scales, scientific phenomena, and forms of expertise to increase ecological understanding and applicability of ecological knowledge (Leahey et al. 2019). Investing in new forms of synthesis science will be key—for example, leveraging advances in artificial intelligence to mine very large data—but equally important is the need to maintain existing infrastructure and resources.

Synthesis is a powerful and productive approach to tackle the most pressing current and future ecological questions. The next generation of synthesis will require new methods and tools to deal with increasingly larger and more diverse data (Hampton et al. 2013), while also requiring researchers to embrace conducting research in teams and use transparent, equitable, and reproducible workflows (Reichman et al. 2011). Synthesis should actively seek to include more diverse people to provide expanded perspectives on continued or emerging ecological issues, which may be more likely given the trend toward greater transdisciplinarity in general but which needs to be set as a priority. Synthesis work will also benefit from coordinated empirical data collection—for example, through research networks such as the Nutrient Network (NutNet; Borer et al. 2014), as well as sustained funding for the empirical research that provides data used by synthesis. Ecological synthesis offers a promising and cost-effective approach to informing evidence-based decisions about managing the unprecedented environmental challenges of the twenty-first century.

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Supplemental material
Supplemental data are available at *BIOSCI* online.

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