Long-Term Studies Contribute Disproportionately to Ecology and Policy

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Long-Term Studies Contribute Disproportionately to Ecology and Policy

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As the contribution for long-term ecological and environmental studies (LTEES) to our understanding of how species and ecosystems respond to a changing global climate becomes more urgent, the relative number and investment in LTEES are declining. To assess the value of LTEES to advancing the field of ecology, we evaluated relationships between citation rates and study duration, as well as the representation of LTEES with the impact factors of 15 ecological journals. We found that the proportionate representation of LTEES increases with journal impact factor and that the positive relationship between citation rate and study duration is stronger as journal impact factor increases. We also found that the representation of LTEES in reports written to inform policy was greater than their representation in the ecological literature and that their authors particularly valued LTEES. We conclude that the relative investment in LTEES by ecologists and funders should be seriously reconsidered for advancing ecology and its contribution to informing environmental policy.

Keywords: climate change, impact factor, citation rate, National Research Council, study duration

Never in the history of scientific inquiry has it been so crucial to understand how species and entire ecosystems respond to environmental change and an ever-growing human population. Long-term ecological and environmental studies (LTEES) hold great promise for identifying and understanding these ecological consequences and for informing management and policy responses. Such knowledge underpins effective approaches to mitigate and adapt to these changes, including the protection of biodiversity, ecosystem functions, and the many ecosystem services relied on by humans. Long-term ecological and environmental studies (LTEES) are essential to characterizing how and why nature is changing, providing a means to understand the regulation and functioning of ecological communities, linking biological patterns to environmental variability, and informing the management of human influences on ecosystems and the services they provide (Likens 1989, McGowan 1990, Cody and Smallwood 1996, Ducklow et al. 2009, Clutton-Brock and Sheldon 2010, Magurran et al. 2010, Nelson et al. 2011, Lindenmayer et al. 2012, Hofmann et al. 2013).

LTEES have contributed profoundly to the development of a multitude of foundational advances in ecology across a diversity of natural ecosystems (figure 1). The inextricable relationship between temperate forest and stream ecosystems emerged from long-term forest manipulations and monitoring at the Hubbard Brook Experimental Forest (figure 1a; Likens et al. 1970). Such studies provided strong evidence of the importance of ecosystem connectivity and how human activities in one ecosystem are transmitted to and influence the biogeochemical processes and the structure, dynamics, and functions (e.g., productivity) of adjacent ecosystems. A theory for the maintenance of species diversity (e.g., unified neutral theory; Hubbell 2001) evolved from the long-term patterns of species dynamics in tropical rainforests, such as those revealed at Barro Colorado Island (figure 1b). Relationships between biodiversity and ecosystem function (e.g., productivity and nutrient cycling) and the ecological

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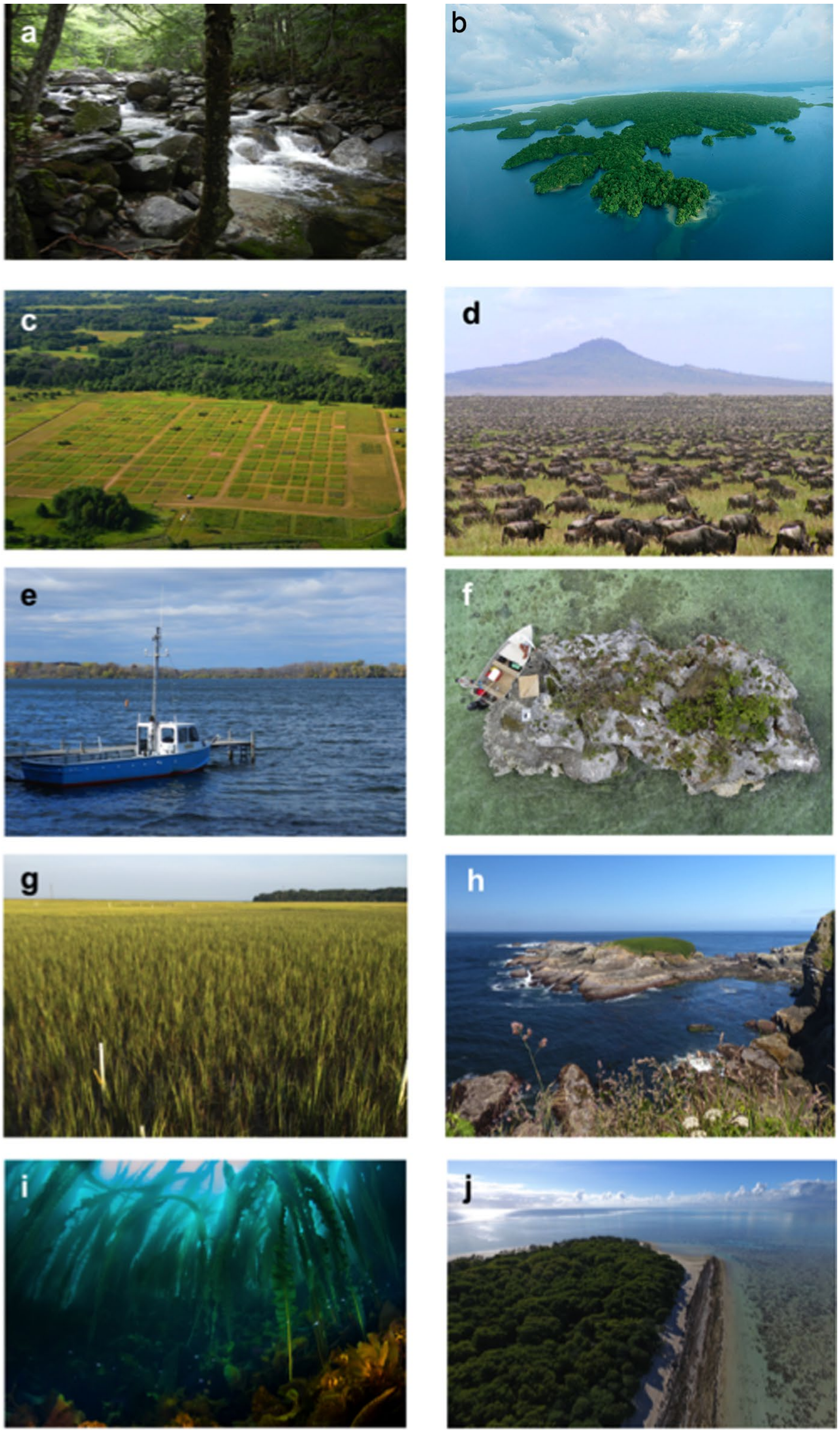

Figure 1. Examples of long-term ecological research sites, which have contributed significantly to advancing ecology and informing environmental policy: (a) temperate forest, Hubbard Brook Experimental Forest (Photograph: Claire Nemes); (b) tropical forest, Barro Colorado Island (Photograph: Christian Ziegler); (c) temperate grassland, Cedar Creek (Photograph: Jacob Miller); (d) tropical savannah, Serengeti (Photograph: Anthony Sinclair); (e) temperate lake, Lake Mendota (Photograph: Stephen Carpenter); (f) tropical islands, Staniel Island (Photograph: Louie Yang); (g) subtropical estuary, Sapelo Island (Photograph: Christine Angelini); (h) temperate rocky intertidal, Tatoosh Island (Photograph: Timothy Wootton); (i) temperate kelp forest, Aleutian Islands (Photograph: Joe Tomoleoni); (j) tropical coral reef, Heron Island (Photograph: Sam Chapman).

mechanisms underpinning those relationships (e.g., competition, life-history traits, functional complementarity, and redundancy) were revealed by long-term manipulations and monitoring of a temperate grassland ecosystem at the Cedar Creek Ecosystem Science Reserve (figure 1c; Tilman 1988, Tilman et al. 2002). Only long-term studies of predator–prey interactions in the tropical savannah ecosystem of the Serengeti revealed how the consequence of these interactions is greatly influenced by the diversity of both predators and prey and their relative body sizes (figure 1d; Sinclair et al. 2003). Long-term studies of community structure in the temperate freshwater lakes of Wisconsin (figure 1e) advanced understanding of the interactions between environmental drivers and trophic cascades (e.g., Carpenter et al. 2001) and revealed rapid shifts in ecosystem states that informed the theory of alternative stable states of ecosystems (Sheffer et al. 2001), spawning research on warning signs of these transitional "tipping points" (Scheffer 2001, Carpenter et al. 2011). Decades of study of lizard and spider assemblages on Caribbean Islands (figure 1f) have shaped our understanding of the concept of niches, resource partitioning, and the interplay between ecological processes (e.g., predation and competition) and environmental conditions for species coexistence and the structure of ecological communities (e.g., Spiller and Schoener 1995, 2008, Schoener and Spiller 1996, Losos et al. 2001). Continued long-term studies building on the seminal works of Odum, Teal, and others (e.g., Odum and Smalley 1959, Teal 1962) on energy and nutrient dynamics in the Sapelo Island saltmarsh (figure 1g) have advanced our understanding of how species interactions affect ecosystem processes. Long-term studies of how species interactions influenced spatial patterns of community structure and species diversity in the rocky intertidal of Tatoosh Island, Washington (figure 1h), inspired the concept of keystone species (Paine 1966). Decadal time series of the abundance of kelp forests (figure 1i), sea urchins, and sea otters across the Aleutian archipelago created one of the best-documented examples of trophic cascades, the crucial role of higher-level predators exerting "top-down" control of community structure (Estes and Palmisano 1974), and links between offshore and onshore ecosystems (Estes et al. 1998). Similarly, multiyear monitoring of the relative abundances of corals on tidal flats of Heron Island, Australia (figure 1j), ultimately revealed outcomes of competitive interactions and the consequences of episodic hurricanes that provided evidence for nonequilibrial mechanisms of the maintenance of diversity in the form of intermediate disturbances (Connell 1978, Connell et al. 2004). Collectively, LTEES have conceived and critically evaluated many of the key conceptual developments in ecology.

LTEES have also proven to be essential for supporting societal and political decisionmaking (Nichols and Williams 2006, Willis et al. 2007, Lindenmayer and Likens 2010, Rohani and King 2010, Schindler and Hilborn 2015). For example, consider where the discussion on global climate change would be in the absence of the Keeling curve, which quantifies the multidecadal rise of atmospheric carbon dioxide levels (Keeling 2008). This study in particular nicely illustrates how very small incremental environmental changes can be detected only because the phenomenon is studied over long periods. Another example is how the characterization of the long-term dynamics of wolf and moose populations on Isle Royale helped establish a nonintervention management policy by the US National Park Service but later identified the potential need of intervention to restoring the integrity of natural ecological processes (Peterson 1999). Ranges of natural variation are identified and temporal trends emerge with prolonged observation. Therefore, LTEES allow us to better understand the inherent variability of natural systems, to discern trends and shifting baselines (Lovett et al. 2007), and to witness rare events and unanticipated ecological surprises (Magnuson 1990, Doak et al. 2008, Lindenmayer et al. 2010). One exemplary case study of these unanticipated discoveries is the classic work of Gene Likens and colleagues at Hubbard Brook Experimental Forest in the northeast United States. Associated with their long-term environmental monitoring program, Likens and colleagues (1996) serendipitously discovered "acid rain" deposition, spawning a series of important publications (Likens et al. 1972, Likens and Bormann 1974) that ultimately influenced the 1990 Clean Air Act Amendment. Another way long-term monitoring studies have influenced environmental policy is their impact on pollution regulations, such as the termination of tributyltin (TBT) in antifouling paints, and how the recovery of species is quantified in order to evaluate the efficacy of these regulations (Hawkins et al. 2010). Other examples include the many cases in which long time series of fisheries stock assessments and fisheries independent surveys, in conjunction with environmental observations, have provided strong evidence of ocean ecosystems responding to climate change and also moving fisheries policy from single-species management to ecosystem-based fisheries management (Edwards et al. 2010). We cannot hope to understand such fundamental ecological phenomena such as forest succession or crucial environmental processes such as climatic interactions and oceanic circulation without long-term studies because they simply operate on longer time frames. Furthermore, because LTEES can capture processes at multiple timescales, conclusions may complement or be more robust and even different from those of studies of shorter durations (Wiens 1981, Brown et al. 2001).

Ironically, as the need for LTEES becomes ever more imperative, the persistence of many existing LTEES has become more precarious, and few new LTEES are being established. For example, although overall funding of ecological studies by the premier funding source for ecological research in the United States, the National Science Foundation (NSF), stagnated over the past decade (2004–2015; figure 2; $R^2(1,10) = .133$, $p = .244$), funding allocated to short-term studies (4 years or fewer) has increased ($R^2(1,10) = .473$, $p = .013$), funding allocated to long-term studies (4 years or longer) has decreased ($R^2(1,10) = .496$,

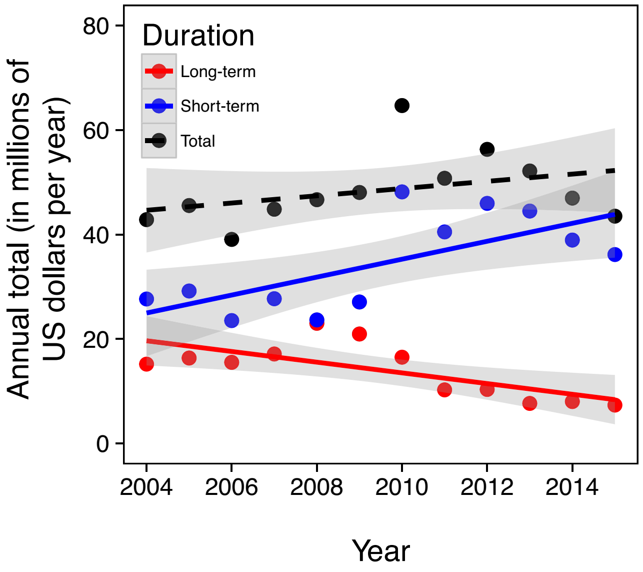

Figure 2. Trends in NSF funding for short- (4 years or shorter) and long-term (longer than 4 years) LTEES studies, as well as total funding, for DEB and Biological Oceanography programs. The solid lines are significant ($p < .05$) trends, and the dashed lines are nonsignificant ($p > .05$) trends. The gray areas represent 95% CI.

$p = .011$), and the trends in overall funding of long-term and short-term studies over this period have deviated significantly (ANCOVA: $F(1) = 4.157$, $p < .0005$; see “Trends in NSF funding of LTEES” in the supplemental materials for detailed methods and analyses). Similarly, during this period, the number of awards allocated to short-term studies have not changed ($R^2(1,10) = .102$, $p = .311$), but the number of awards allocated to long-term studies has significantly decreased ($R^2(1,10) = .547$, $p = .006$), resulting again in a significant deviation in the number of awards allocated to long-term versus short-term studies over the last decade (ANCOVA: $F(1) = 6.951$, $p = .016$; see “Trends in NSF funding of LTEES” in the supplemental materials). Moreover, the average award amount for individual long-term (longer than 4 years) studies has not significantly increased ($R^2(1,10) = .001$, $p = .921$), whereas the average award amount for individual short-term (4 years or fewer) has significantly increased ($R^2(1,10) = .426$, $p = .0215$). Although these award amounts are converging, typical long-term studies continue to include many more co-investigators (e.g., the NSF’s Long-Term Ecological Research, LTER, programs).

Whereas this evaluation of LTEES funding by the US National Science Foundation is illustrative, other important examples include the precarious support of some of the most important LTEES in Canada as well. Perhaps the most disconcerting example is the recent funding dynamics of the Experimental Lakes Area (ELA), a premier ecological research institution in Canada, involving both ecosystem experiments and long-term monitoring. Established in 1968, funding by the federal government was terminated in 2012. Fortunately, a privately funded organization, the International Institute for Sustainable Development, agreed to assume operation of the facility, and provincial governments stepped in to bridge the funding gap. In 2014, the federal government once again provided some partial support for ELA. Similarly, the Department of Fisheries and Oceans (DFO), Canada, maintained among the finest and most valuable long-term records of Sockeye salmon population dynamics throughout British Columbia, Canada. However, recently, these time series, some of them spanning over 45 years, have been terminated, including the only Sockeye salmon stocks along a 1000-kilometer coastline for which freshwater and marine survival could be partitioned. Such examples of the discontinuation of highly invested, extremely valuable LTEES are not confined to the governmental funding and research institutions of the United States or Canada but are instead symptomatic of trends in many parts of the world as these organizations face difficult funding decisions.

In general, the declining support for LTEES by funding organizations such as the NSF reflects several contributing factors. Historically, support for LTEES in the scientific community has been contentious (Legg and Nagy 2006, Lindenmayer and Likens 2009, Fancy and Bennetts 2012). Critics have noted poorly defined questions and hypotheses and the inflexibility of sampling designs for addressing emerging environmental problems. Funders are hesitant to invest in LTEES that largely support the same investigators repeatedly for prolonged periods and prefer distributing funds across a greater number of researchers whose short-term studies can more rapidly address pressing and emerging ecological and policy issues. Moreover, in academia, young scientists are rewarded for frequent publications and may be increasingly hesitant to initiate and invest in studies whose publishable products will be delayed. Nonetheless, we suggest that funding decisions should reflect the relative value of short- and long-term ecological studies as perceived by the science community, including those involved in the process of informing policy.

Here, we demonstrate the disproportionate value of LTEES to science and for informing policy relative to funding allocations that favor short-term studies. To evaluate the perceived value of LTEES to both science and policy, we tested the following hypotheses: (a) The representation of LTEES (the percentage of LTEES of all ecological studies) increases in journals that publish peer-reviewed articles of greater perceived value to the scientific community (as is judged by a journal’s impact factor). (b) LTEES contribute disproportionately to a journal’s higher impact factor (i.e., the citation rates of LTEES increases with study duration, and this relationship increases with the impact factor of a journal). To determine whether LTEES are more highly valued in reports whose purpose is to inform decisionmakers, we also tested the hypotheses that (c) the representation of LTEES in US National Research Council (NRC) reports was

Table 1. A list of journals used to test for relationships between the citation rate and the study duration (2006 only) and between the study duration and the impact factor of the journal (2006 and 2010).

Number	Impact factor 2006	Impact factor 2010	Journal
1	1.92	1.91	*Journal of Experimental Marine Biology and Ecology*
2	2.29	2.48	*Marine Ecology Progress Series*
3	3.33	3.52	*Oecologia*
4	3.38	3.39	*Oikos*
5	NA	4.41	*PLOS One*
6	3.47	4.28	*Ecological Applications*
7	3.76	4.89	*Conservation Biology*
8	4.53	4.97	*Journal of Applied Ecology*
9	4.78	5.07	*Ecology*
10	7.10	5.93	*Ecological Monographs*
11	7.61	15.25	*Ecology Letters*
12	9.64	9.77	*Proceedings of the National Academy of Sciences (PNAS)*
13	10.99	10.26	*Current Biology*
14	26.68	36.10	*Nature*
15	30.03	31.38	*Science*

Note: Most journals are exclusively ecological, and others frequently publish ecological articles (Science, Nature, Current Biology, PNAS, PLOS ONE). The journals were selected to encompass a range of impact factors. NA indicates that the journal did not exist that year.

greater than their representation in the general scientific literature and that (d) the authors of those NRC reports particularly valued LTEES in their analyses and reports. For our tests of these hypotheses, we restricted our analyses to the ecological subset of NRC reports.

Perceived value of LTEES to advancing the field of ecology

We used two approaches to test our first hypothesis that the representation of long-term studies increases with the perceived importance of a journal, applying a categorical definition of LTEES (longer than 4 years) and applying study duration as a continuous variable. We used a linear regression to test the relationship between the percentage of published studies categorized as long term (longer than 4 years, hereafter “percent long-term studies”) and journal impact factor (IF) for journals reviewed in both 2006 and 2010. We then used ANCOVA to test for any differences in this relationship between 2006 and 2010 (see “Percent long-term studies and journal impact factor” in the supplemental materials). We also used a linear regression to test for a relationship between mean study duration (in years) and a journal’s impact factor for both 2006 and 2010.

To test our second hypothesis that LTEES contribute disproportionately to the impact factor of a journal, we used a two-factor ANOVA to test for an interaction between study duration and journal impact factor on the citation rate of articles in each of the journals reviewed in 2006 and 2010 (see “Contribution of LTEES to citation rates of higher impact journals” in the supplemental materials). We determined the study duration of all articles published by 15 representative ecological journals in 2 years (2006 and 2010; table 1). We chose these 2 years for our analyses because our review was initiated in late (September–December) 2012 for 2006 studies and September 2016 for 2010 studies, and citation rates tend to peak well beyond 2 years after publication (Glånzel and Moed 2002).

Study duration was evaluated as both a continuous and a categorical (LTEES longer than 4 years in duration) variable using a minimum resolution of 1 year (see “Estimate of study durations in the ecological literature” in the supplemental materials). Four years is a meaningful delineation between long- and short-term studies because it represents a typical maximum length of many NSF grants and graduate research studies. Nonetheless, we assessed the sensitivity of our results to this categorization by comparing the slope of relationships between journal impact factor and the percentage of LTEES using LTEES definitions of durations longer than 4 to longer than 9 years and found no difference in these relationships (see “Categorization of LTEES” in the supplemental materials). Our analyses of articles from both 2006 and 2010 allowed us to determine the repeatability of the observed relationships between duration and both citation rate and journal impact factor.

Although study duration can be defined and quantified in various ways and applied to various ecological approaches (e.g., field, modeling, reviews, meta-analyses, and paleoecological), we were interested in the perceived value of the temporal and financial investment in prolonged research programs. Not all ecological studies are pertinent to this evaluation. For example, paleoecological studies were excluded to avoid outliers that would create a bias toward longer study durations and because of great differences in the financial investment related to methods used in these studies and modern ecological studies. We therefore considered only empirical experimental and observational studies either in the lab or field and quantified their duration by the total number of years in which sampling was actually conducted (e.g., 5 years of data collection in sequential years and five intermittent annual samples over a 20-year study duration were both categorized as a 5-year study). Nonetheless, study duration and study span (beginning to end of overall study period) were tightly correlated (see “Estimate of study durations in the ecological literature” in the supplemental materials). We also estimated the error among journal reviewers in their estimates of study duration. Of the total 18% error in estimates of study duration between observers, 48% was error by a single year and therefore had little influence on comparisons of long- and short-duration studies (see “Categorization of LTEES” in the supplemental materials).

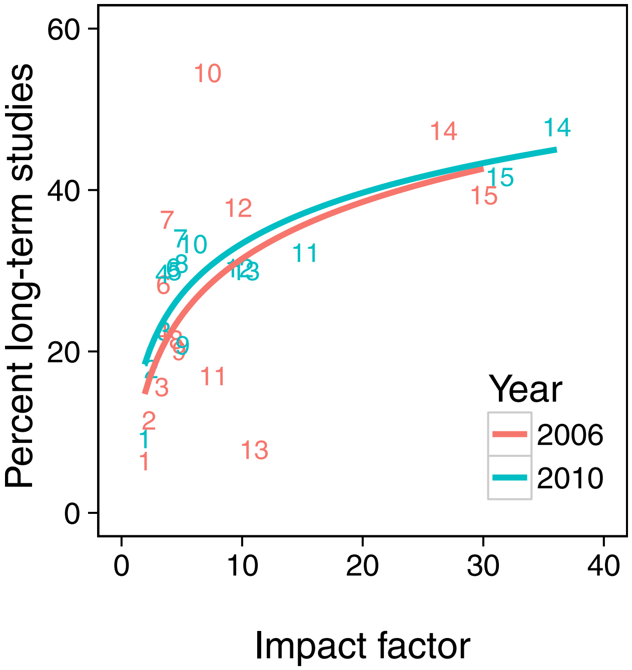

Figure 3. The relationship between a journal's impact factor and the percentage of its articles whose studies exceeded a duration of 4 years, averaged over 2 years (2006 and 2010). The numbers indicate individual journals (table 1).

Impact factors (equation 1) are commonly used to assess the relative importance of journals in relation to others and are commonly calculated as the following:

$$IF_t = (A_{t-1} + A_{t-2}) * (B_{t-1} + B_{t-2})^{-1} \qquad \text{Equation 1}$$

where the impact factor, IF, reflects the ratio of the number of citations, A, from previous years and the number of citable items, B, in those years (Journal Citation Reports, Thomson Reuters, New York City, United States). Journal impact scores were obtained from the Web of Science in 2012 for 2006 and in September 2016 for 2010.

The percentage of articles (2006 and 2010 combined) in a journal consisting of LTEES increased with journal impact factor (figure 3; $R^2(1,27) = .483$, $p < .0001$; see "Percent long-term studies and journal impact factor" in the supplemental materials). Similarly, we detected a positive relationship between a journal's impact factor and the mean duration of its published studies (2006: $R^2(1,13) = .454$, $p = .008$; 2010: $R^2(1,14) = .615$, $p = .0005$). Moreover, with respect to our second hypothesis that LTEES contribute disproportionately to a journal's impact factor, we found that the positive relationship between citation rate and study duration was stronger as journal impact factor increased (figure 4a–b; two-factor ANOVA, impact factor*study duration interaction; 2006: $F(1) = 21.627$, $p < .0001$; 2010: $F(1) = 3.968$, $p = .0465$; see "Contribution of LTEES to citation rates of higher-impact journals" in the supplemental materials). This relationship was consistent for both years of journals reviewed. These analyses revealed that LTEES therefore contribute disproportionately to the perceived value of articles in higher impact journals (2006), however, the pattern was not consistent between the two years sampled.

Perceived value of LTEES for informing environmental policy

We used NRC reports to evaluate the importance of LTEES for informing environmental policy by testing the hypotheses that (a) the duration of studies cited in reports is greater than those of studies published in the general ecological literature and that (b) LTEES are represented disproportionately in NRC reports relative to their frequency in the scientific literature. NRC reports are considered among the most influential sources of scientific synthesis for informing US environmental policy. Each NRC report serves as a topic-specific synthesis of the scientific literature and is conducted for the specific purpose of informing policymakers. We restricted our analyses to all 44 ecologically relevant NRC reports published in 2010. All studies cited within each NRC report that met the same criteria we used in our consideration of journal impact factors were considered, representing publications from the years 1951–2010 from 333 different journals. To directly compare the durations of NRC-cited studies with those published in the sampled ecological literature, we accounted for a positive relationship among study duration and publication year, ecosystem-specific differences, and random-effect differences between NRC reports. We did so by using the duration residuals of a linear mixed model including these covariates and standardizing these to the year 2006 (see "Evaluation of LTEES contribution to policy-informing literature" in the supplemental materials).

Each NRC report was reviewed by two individuals. Each reviewer independently counted the total number of references cited in the report and identified all the peer-reviewed ecological studies. The two reviewers then reconciled the differences between their tallies. For a subset of interdisciplinary papers for which ecological classification by a reviewer pair proved difficult, a larger number of reviewers were consulted to reach a consensus. Similar to the approach we used for the ecological journals, error in the assignment of study durations among reviewers was evaluated by having all reviewers assign durations from the same set of 20 references. Overall, the pooled standard deviation of study duration from these references was 0.722 years, which is less than the defined minimum duration of 1 year.

The NRC reports and ecological literature cited studies conducted over different time periods and across a diversity of ecosystems, so we tested for relationships between study year or ecosystem and the duration of cited studies to determine whether differences in the range of years and the proportionate representation of ecosystems (freshwater, marine, terrestrial, or "multiple") in studies cited in the

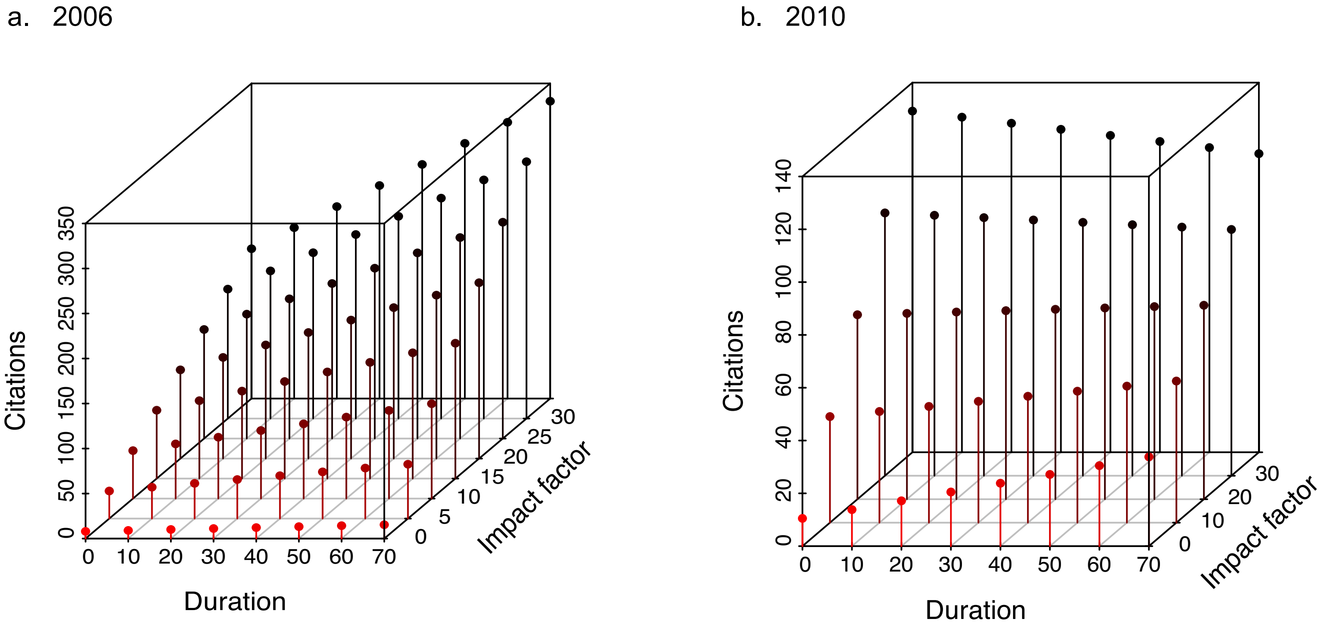

Figure 4. Modeled relationship between a journal's impact factor and the rate at which the number of citations of an article published in (a) 2006 and (b) 2010 increased with study duration (supplemental table s1). The lines under the model points serve as references for the orientation of axes.

ecological literature and the NRC reports might confound our comparisons. Study duration differed with both year and ecosystem, and study duration was related to both year and ecosystem type in the general ecological literature. However, there was little indication that study duration varied by year or ecosystem in studies cited in NRC reports (see "Relationship between year of publication, ecosystem, and study duration" in the supplemental materials). To account for the differences in study duration by ecosystem and publication year, the residuals from these models were used as the response variables. We used a two-sided t-test to assess the difference between mean residual durations of the two data sets. Our null hypothesis was that the means of the residual study durations from the general literature and the literature extracted from the NRC reports would be the same.

The median duration of NRC-cited studies was only 1.30 years longer than studies in the scientific literature (t-test, $t(4780) = 7.22$, $p < .001$, 95% confidence intervals [CI] = 1.21–1.39). However, this seemingly small difference in median study durations belie a far greater difference in the representation of LTEES in NRC reports because the frequency distributions of study durations were highly skewed and heavy tailed. A second analysis considering the difference in the cumulative frequency distributions of study durations in NRC-cited studies and the scientific literature illustrates how NRC reports disproportionately cited studies of greater duration (figure 5). The longest-duration studies (greater than the 75th percentile) from NRC reports were 5 to 40 years longer in duration than the same percentile in the general scientific literature.

To gain further insight into the process by which short- versus long-term ecological studies were selected by NRC report authors, we surveyed all authors of the 44 NRC reports considered (see "NRC author survey methods" in the supplemental materials). NRC reports are written by experts representing academia, government, industry, and nonprofit organizations, whose perception of LTEES may differ (National Academies 2015). Of the 480 authors contacted, 114 (23.75%) responded anonymously to a series of questions (Likert scale and rank style) assessing their opinions on (a) the value of long-term ecological research and its contribution to scientific knowledge and policy decisions, (b) the importance of study durations for informing NRC report recommendations, and (c) the importance of a study's duration for citation in a report. We used these answers to assess whether a disproportionate number of authors expressed preference for LTEES and whether self-reported ecologists versus nonecologists differed in their opinions regarding the relative importance of LTEES.

Our survey revealed that NRC report authors agreed that (a) study duration was an important criterion for citation more frequently than expected under the null hypothesis (null = 0, 95% CI = 0.32–0.60, $n = 62$, $p < .0001$), (b) authors were more inclined to cite long-term studies than short-term studies (null = 0, 95% CI = 0.15–0.32, $n = 109$, $p < .0001$), (c) long-term ecological data sets provide information that short-term studies cannot (null = 0, 95% CI = 0.59–0.73, $n = 109$, $p < .0001$), and (d) long-term studies are important for informing policy (null = 0, 95% CI = 0.65–0.77, $n = 109$, $p < .0001$). For more detailed results, see "NRC author survey results" in the supplemental materials. When we

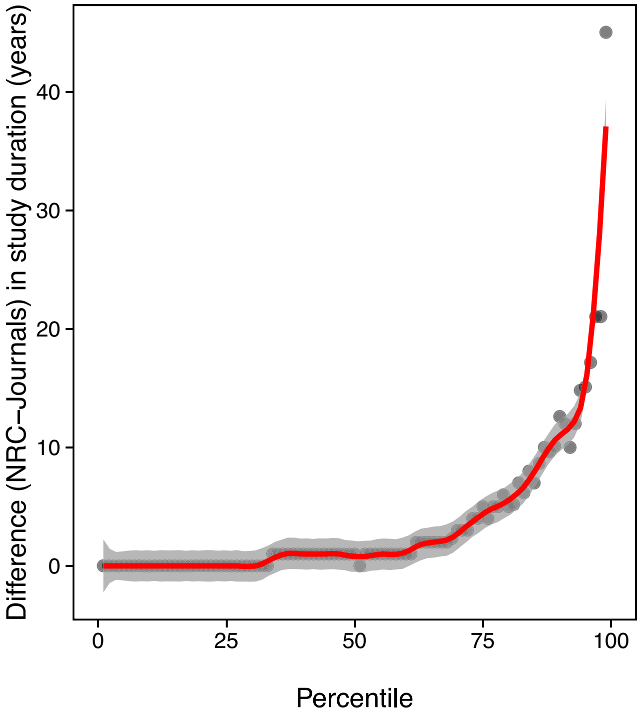

Figure 5. The difference in the cumulative frequency distribution of study durations between studies cited in NRC reports and the scientific ecological literature. The line was fitted using a loess smoother function. The relationship illustrates the disproportionate frequency with which LTEES are used to inform policymaking decisions; 25% of NRC-cited studies had durations of 5 to more than 40 years greater than the equivalent percentile of studies in the scientific literature.

compare responses between ecologist versus nonecologists, there was a general, albeit nonsignificant (all $p > .05$), trend of ecologists viewing the importance of long-term ecological data sets more favorably.

These same NRC authors also ranked studies of more than 1 year as more important to the recommendations of their report relative to studies with shorter durations based on ranked analyses of increasing study duration ($\chi^2(3) = 38.08$, $p < .0001$, all pairwise comparisons with "less than 1 year" differed at $p < .0001$). When these values were broken down by ecologists versus nonecologists, there was a tendency for ecologists to cite fewer short-term (1-year study duration; $p = .0166$) and more long-term (6- to 10-year study duration; $p = .0018$) studies compared with nonecologists. However, when authors were asked how often they cited studies with different durations, they reported citing studies of 2–5 years' duration most frequently. This mismatch between citation frequency and preference for study duration suggests a relative scarcity of long-term ecological studies in the literature. This was also supported by the fact that the majority (56%) of ecologists who reported infrequent citation of long-duration studies of 6 or more years explained that doing so was because of the lower availability of long-term studies in the literature. For more detailed results of these analyses, see "NRC author survey results" in the supplemental materials.

Conclusions

As was indicated by the disproportionate frequency with which LTEES are cited and their disproportionate occurrence and contributions in the more highly regarded scientific journals, our results indicate that the scientific community values LTEES more highly than shorter-term ecological studies. Within the scientific community, there is growing appreciation and demand for time series with durations well beyond those generated by the typical study currently being funded. The rapidly expanding capacity to forecast system dynamics, detect causality between variables, and forewarn of impending tipping points when longer time series are available underpins this growing interest (Scheffer 2010, Ye et al. 2015). Indeed, even among the long time series that do exist, most are still limited to single or paired species, with very few representing the community-wide studies necessary to advance our understanding of the complex dynamics of multispecies assemblages and ecosystems. However, in recognition of the importance of data sets generated by LTEES, the science community is exploring the unique nuances of archiving and sharing these valuable data sets (Mills et al. 2015, Mills et al. 2016, Whitlock et al. 2016).

Our review of NRC reports further indicates that LTEES play a vital role in informing environmental policy, with NRC reports disproportionately citing LTEES relative to their frequency of citation in the ecological literature and NRC authors agreeing that LTEES contribute unique information to the recommendations of their reports. Notably, the survey of NRC authors also highlighted a mismatch between the demand and availability of LTEES. This suggests that the paucity of LTEES in the scientific literature comes at a significant cost to not only the scientific advancement of ecology and its related fields but also the capacity of science to inform policymakers. Together, these results support the assertion that both private and governmental funding sources should reverse their declining allocations of funds to long-term ecological studies.

Past critiques of LTEES have spurred much thought by the ecological community of the key elements of productive, sustainable LTEES (box 1; Lindenmayer and Likens 2009, McDonald-Madden et al. 2010, Peters 2010). These studies are designed to address questions or hypotheses that pertain to issues of significant societal interest (i.e., that inform management and policy decisions) and that require long-term ecological and environmental time series. They are multidisciplinary, especially those that span multiple ecosystems or explore the complexity of coupled social–ecological systems. They integrate short- and long-term experimental, observational, and modeling components. They are initiated with well-designed data-management, -archiving, and -dissemination systems. Core time series maintain consistent sampling designs and protocols that ensure the integrity of

Box 1. A recommended attributes of sustainable, productive LTEES largely drawn from the ecological literature (see text for citations).

Question/hypothesis-based purpose

Ensure that the purpose and design of a LTEES is motivated by well-defined questions and associated hypotheses.

Both basic and applied purposes

Include both basic and applied purposes (questions) to increase the value of an LTEES and breadth of interested participants and funding sources.

Consistent core sampling design and protocols

Ensure that core sampling design criteria (spatial and temporal) and protocols are consistent through time to maintain the integrity of a time series. Any new designs and methods should be gradually transitioned to with calibration to evaluate comparability and compatibility of the time series.

Consistency and quality of data collection

Establish a rigorous system for maintaining consistency and reliability of data collection and quality control over the long term that is robust to turnover of project personnel. This includes the training and evaluation of data collectors.

Adaptability of sampling design and protocols

Ensure capacity to adopt additional designs and protocols to enhance its relevance by addressing emergent and topical questions and hypotheses.

Documentation

Maintain rigorous and detailed documentation of sampling designs, data collection methods, instrumentation, calibrations, environmental conditions and other metadata to inform the proper use and interpretation of data.

Data management and dissemination

Design and support a well-developed and adaptable data management and data dissemination program throughout the lifetime of the LTEES. This includes a strong online presence.

Attractive and inclusive participation by the scientific community and others

Develop means (e.g., workshops, website, outreach) for engaging others in the research community, managers, stakeholders, citizen science and others with emphasis on recruiting new young researchers.

Management structure

Implement an adaptable and functional management and governance structure that is responsible for strategic research planning, resource allocation, administrative policies, and staffing throughout the lifetime of the LTEES.

Rigorous funding structure

Identify and establish long-term reliable and resilient funding sources in advance of initiating an LTEES. Establish mechanisms for identifying and pursuing additional sources of funding throughout the lifetime of the LTEES (e.g., outreach products and efforts).

Complementary research programs

Foster and integrate a diversity of multi- and interdisciplinary research approaches (e.g., short and long-term experiments, modeling, coupled biological and physical observations, coupled socio-ecological investigations).

Educational component

Create educational components that expose future generations of scientists and others to the value of LTEES at several levels (visiting researchers and teachers, post-doctoral fellows, graduate students, undergraduates, K-12).

the long-term data sets. These and other design elements enable LTEES to simultaneously address those questions that require long time series but are flexible enough to address emerging and timely issues that draw on insights generated by the long time series. They attract young investigators with the opportunity to contribute to and quickly benefit from the intuitive understanding of systems that only long time series generate. Creative designs that leverage and integrate short- and long-term studies can resolve past concerns raised by critics of poorly designed long-term studies.

Not surprisingly, all of these elements of continuously informative LTEES have become crucial components of the NSF's LTER (*www.lternet.edu/lter-sites*) program (Callahan 1984, Franklin et al. 1990) and have contributed importantly to our understanding of the ecological consequences of a changing global climate. However, across the 28 LTER sites, the majority confined to the United States, there is representation of only a fraction of earth's ecosystems and they do not capture the large-scale geographic variation typical of ecosystems. Therefore, the inferences generated by this small sample size of long-term research programs are constrained by the limited funding provided by governmental and nongovernmental funding sources. The conclusions generated by our analyses argue strongly for greater funding for a larger global network of LTEES modeled on many of the attributes of the NSF's LTER program. Fortunately, the more recent establishment of Long-Term Ecosystem Research in Europe (LTER-Europe; *www.lter-europe.net*) and the International Long Term Ecological Research (iLTER; *www.ilternet.edu*) programs will provide a more global characterization of long-term ecosystem dynamics.

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Supplemental material

Supplementary data are available at *BIOSCI* online.

References cited

Brown JH, Whitham TG, Ernest SKM, Gehring CA. 2001. Complex species interactions and the dynamics of ecological systems: Long-term experiments. Science 293: 643–650.

Callahan JT. 1984. Long-term ecological research. BioScience 34: 363–367.

Carpenter SR, Cole JJ, Hodgson JR, Kitchell JF, Pace ML, Bade D, Cottingham KL, Essington TE, Houser JN, Schindler DE. 2001. Trophic cascades, nutrients, and lake productivity: Whole-lake experiments. Ecological Monographs 71: 163–186.

Carpenter SR, et al. 2011. Early warnings of regime shifts: A whole-ecosystem experiment. Science 332: 1079–1082.

Clutton-Brock T, Sheldon BC. 2010. Individuals and populations: The role of long-term, individual-based studies of animals in ecology and evolutionary biology. Trends in Ecology and Evolution 25: 562–573.

Cody ML, Smallwood JA, eds. 1996. Long-Term Studies of Vertebrate Communities. Academic Press.

Connell JH. 1978. Diversity in tropical rain forests and coral reefs. Science 199: 1302–1310.

Connell JH, Hughes TP, Wallace CC, Tanner JE, Harms KE, Kerr AM. 2004. A long-term study of competition and diversity of corals. Ecological Monographs 74: 179–210.

Doak DF, et al. 2008. Understanding and predicting ecological dynamics: Are major surprises inevitable? Ecology 89: 952–961.

Ducklow HW, Doney SC, Steinberg DK. 2009. Contributions of long-term research and time-series observations to marine ecology and biogeochemistry. Annual Review of Marine Science 1: 279–302.

Edwards M, Beaugrand G, Hays GC, Koslow JA, Richardson AJ. 2010. Multi-decadal oceanic ecological datasets and their application in marine policy and management. Trends in Ecology and Evolution 25: 602–610.

Estes JA, Palmisano JF. 1974. Sea otters: Their role in structuring nearshore communities. Science 185: 1058–1060.

Estes JA, Tinker MT, Williams TM, Doak DF. 1998. Killer whale predation on sea otters linking oceanic and nearshore ecosystems. Science 282: 473–476.

Fancy SG, Bennetts RE. 2012. Institutionalizing an effective long-term monitoring program in the US National Park Service. Pages 481–497 in Gitzen RA, Millspaugh JJ, Cooper AB, Licht DS, eds. Design and Analysis of Long-Term Ecological Monitoring Studies. Cambridge University Press.

Franklin JF, Bledsoe CS, Callahan JT. 1990. Contributions of the long-term ecological research program. BioScience 40: 509–523.

Glänzel W, Moed HF. 2002. Journal impact measures in bibliometric research. Scientometrics 53: 171–193.

Hawkins SJ, Gibbs PE, Pope ND, Burt GR, Chesman BS, Bray S, Proud SV, Spence SK, Southward AJ, Langston WJ. 2002. Recovery of polluted ecosystems: The case for long-term studies. Marine Environmental Research 54: 215–222.

Hofmann GE, Blanchette CA, Rivest EB, Kapsenberg L. 2013. Taking the pulse of marine ecosystems: The importance of coupling long-term physical and biological observations in the context of global change biology. Oceanography 26: 140–148.

Hubbell SP. 2001. The Unified Neutral Theory of Biodiversity and Biogeography. Princeton University Press.

Keeling R. 2008. Recording Earth's vital signs. Science 319: 1771–1772.

Legg CJ, Nagy L. 2006. Why most conservation monitoring is, but need not be, a waste of time. Journal of Environmental Management 78: 194–199.

Likens GE, ed. 1989. Long-Term Studies in Ecology: Approaches and Alternatives. Springer.

Likens GE, Bormann FH. 1974. Acid rain: A serious regional environmental problem. Science 184: 1176–1179.

Likens GE, Bormann FH, Johnson NM, Fisher DW, Pierce RS. 1970. Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook Watershed–Ecosystem. Ecological Monographs 40: 23–47.

Likens GE, Bormann FH, Johnson NM. 1972. Acid rain. Environment 14: 33–40.

Likens GE, Driscoll CT, Buso DC. 1996. Long-term effects of acid rain: Response and recovery of a forest ecosystem. Science 272: 244–246.

Lindenmayer DB, Likens GE. 2009. Adaptive monitoring: A new paradigm for long-term research and monitoring. Trends in Ecology and Evolution 24: 482–486.

———. 2010. The science and application of ecological monitoring. Biological Conservation 143: 1317–1328.

Lindenmayer DB, Likens GE, Krebs CJ, Hobbs RJ. 2010. Improved probability of detection of ecological "surprises." Proceedings of the National Academy of Sciences 107: 21957–21962.

Lindenmayer DB, et al. 2012. Value of long-term ecological studies. Austral Ecology 37: 745–757.

Losos JB, Schoener TW, Warheit KI, Creer D. 2001. Experimental studies of adaptive differentiation in Bahamian *Anolis* lizards. Genetica 112–113: 399–415.

Lovett GM, Burns DA, Driscoll CT, Jenkins JC, Mitchell MJ, Rustad L, Shanley JB, Likens GE, Haeuber R. 2007. Who needs environmental monitoring? Frontiers in Ecology and the Environment 5: 253–260.

Magnuson JJ. 1990. Long-term ecological research and the invisible present. BioScience 40: 495–501.

Magurran AE, Baillie SR, Buckland ST, Dick JM, Elston DA, Scott EM, Smith RI, Somerfield PJ, Watt AD. 2010. Long-term datasets in biodiversity research and monitoring: Assessing change in ecological communities through time. Trends in Ecology and Evolution 25: 574–582.

McDonald-Madden E, Baxter PWJ, Fuller RA, Martin TG, Game ET, Montambault J, Possingham HP. 2010. Monitoring does not always count. Trends in Ecology and Evolution 25: 547–550.

McGowan JA. 1990. Climate and change in oceanic ecosystems: The value of time-series data. Trends in Ecology and Evolution 5: 293–299.

Mills JA, et al. 2015. Archiving primary data: Solutions for long-term studies. Trends in Ecology and Evolution 30: 581–589.

Mills JA, et al. 2016. Solutions for archiving data in long-term studies: A reply to Whitlock et al. Trends in Ecology and Evolution 31: 85–87.

[National Academies] National Academies of Science, Engineering, and Medicine. 2015. Our Study Process. National Academies. (6 July 2015; *www.nationalacademies.org/studyprocess/index.html*)

Nelson MP, Vucetich JA, Peterson RO, Vucetich LM. 2011. The Isle Royale Wolf–Moose Project (1958–present) and the wonder of long-term ecological research. Endeavour 35: 30–38.

Nichols JD, Williams BK. 2006. Monitoring for conservation. Trends in Ecology and Evolution 21: 668–673.

Odum EP, Smalley AE. 1959. Comparison of population energy flow of a herbivorous and a deposit-feeding invertebrate in a salt marsh ecosystem. Proceedings of the National Academy of Sciences 45: 617–622.

Paine RT. 1966. Food web complexity and species diversity. American Naturalist 100: 66–75.

Peters DP. 2010. Accessible ecology: Synthesis of the long, deep, and broad. Trends in Ecology and Evolution 25: 592–601.

Peterson RO. 1999. Wolf–moose interaction on Isle Royale: The end of natural regulation? Ecological Applications 9: 10–16.

Rohani P, King AA. 2010. Never mind the length, feel the quality: The impact of long-term epidemiological data sets on theory, application and policy. Trends in Ecology and Evolution 25: 611–618.

Scheffer M. 2010. Complex systems: Foreseeing tipping points. Nature 467: 411–412.

Scheffer M, Carpenter S, Foley JA, Folke C, Walker B. 2001. Catastrophic shifts in ecosystems. Nature 413: 591–596.

Schindler DE, Hilborn R. 2015. Prediction, precaution, and policy under global change. Science 347: 953–954.

Schoener TW, Spiller DA. 1996. Devastation of prey diversity by experimentally introduced predators in the field. Nature 381: 691–694.

Sinclair ARE, Mduma S, Brashares JS. 2003. Patterns of predation in a diverse predator–prey system. Nature 425: 288–290.

Spiller DA, Schoener TW. 1995. Long-term variation in the effect of lizards on spider density is linked to rainfall. Oecologia 103: 133–139.

———. 2008. Climatic control of trophic interaction strength: The effect of lizards on spiders Oecologia 154: 763–771.

Teal JM. 1962. Energy flow in the salt marsh ecosystem of Georgia. Ecology 43: 614–624.

Tilman D. 1988. Plant Strategies and the Dynamics and Structure of Plant Communities. Princeton University Press.

Tilman D, Knops J, Wedin D, Reich P. 2002. Experimental and observational studies of diversity, productivity, and stability. Pages 42–70 in Kinzig AP, Pacala SW, Tilman D, eds. The Functional Consequences of Biodiversity: Empirical Progress and Theoretical Extensions. Princeton University Press.

Whitlock MC, et al. 2016. A balanced data archiving policy for long-term studies. Trends in Ecology and Evolution 31: 84–85.

Wiens JA. 1981. Single-sample surveys of communities: Are the revealed patterns real? American Naturalist 117: 90–98.

Willis KJ, Araújo MB, Bennett KD, Figueroa-Rangel B, Froyd CA, Myers N. 2007. How can a knowledge of the past help to conserve the future? Biodiversity conservation and the relevance of long-term studies. Philosophical Transactions of the Royal Society B 362: 175–186.

Ye H, Beamish RJ, Glaser SM, Grant SC, Hsieh CH, Richards LJ, Schnute JT, Sugihara G. 2015. Equation-free mechanistic ecosystem forecasting using empirical dynamic modeling. Proceedings of the National Academy of Sciences 112: E1569–E1576.

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