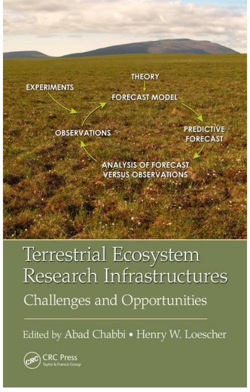

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Role of Long-Term Experiments in Understanding Ecosystem Response to Global Change

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Role of Long-Term Experiments in Understanding Ecosystem Response to Global Change

H. Henry Janzen and Benjamin H. Ellert

CONTENTS

19.1 Introduction

For many decades, scientists have sought to understand how ecosystems respond to stresses, especially to those imposed by humans. Already a century-and-a-half ago, for example, Marsh (1864) documented mounting evidence of how human activities were degrading the biosphere and looked for ways of reducing those damages. Now, understanding change has assumed even greater urgency because human stresses on ecosystems, locally and globally, have intensified, driven by growing population and expanding demands (Carpenter et al. 2009; Chapin et al. 2009; Collins and Childers 2014; Gunderson and Folke 2011). In the past, most human effects on ecosystems occurred locally; now, they often extend globally, notably through effects on atmospheric CO_2, which is rapidly increasing, affecting climates around the world (Le Quéré et al. 2015).

Ecosystem responses to human disturbance, however, can be properly understood only by studying them for periods of several decades or longer (Carpenter 2002; Knapp et al. 2012; Kümmerer et al. 2010; White 2013). Short-term studies, of several months or years, are indispensable in elucidating underlying processes and mechanisms, but they cannot reveal the eventual, final response. Many ecosystem properties change only slowly and the full response is seen only after time scales of a century; for example, responses of soil carbon to management change may unfold over many decades and may not even be discernible until 5 or 10 years have passed (Ellert et al. 2000). Furthermore, some ecosystem responses may be episodic, affected by fluctuating weather or other variables, so studies lasting only a few years may miss them entirely (Franklin 1989). Other responses may be delayed for several decades until a critical "tipping point" is reached (Villa et al. 2014); for example, after cultivating grassland, the cultivated land may initially be highly productive, but yields may eventually decline as native fertility is depleted (Janzen 2001). For these and other reasons, long-term experimental sites have been invaluable to ecologists in understanding ecosystem change and will likely remain so in the coming decades (Mooney et al. 2009; Southwood 1994). Indeed, given the intensity of projected climate and other global changes, some of which remain unpredictable (Boyd 2012), such long-term ecological sites (LTES) may become even more important in the future (Richter et al. 2007).

In light of the intensifying stresses on ecosystems and the long response time of ecosystems to these pressures, this brief review will address the following objectives: (1) to define "long-term ecological site or sites," (2) to propose some attributes that enhance the usefulness and longevity of such studies, and (3) to proffer examples of research questions that may merit more attention in long-term experiments.

19.2 Definition of Long-Term Ecological Sites

An LTES, as the phrase is used here, is a designated area of land maintained for long durations to measure eventual responses to human and other related stresses. By Tansley's definition, an ecosystem is any assemblage of biota and their myriad interactions with each other and their physical habitat (Tansley 1935). Strictly speaking, it can be of almost any size (Grove et al. 2013; Tansley 1935; Willis 1997), depending on questions being asked, so LTES may range in scale from a series of bottles buried in soil by Beal in 1879 (Greenfieldboyce 2012; Telewski and Zeevaart 2002) to a watershed (e.g., Peters et al. 2013) to the entire planet, as in monitoring sites for atmospheric CO_2 (Keeling 2008). Typically, however, LTES have areas measured in units of m^2 or ha, large enough to reflect the influences of a farmer, forester, or other ecosystem manager, but small enough to allow representative sampling. If the area is too small, it may be too susceptible to outside interferences (e.g., border effects) or inadequately represent the larger ecosystem; if the area is too large, sampling of ecosystem properties becomes prohibitively demanding because of spatial heterogeneity.

Often, LTES have more than one "treatment," each reflecting a distinct ecosystem or land use, thus allowing comparisons among ecosystems as well as measuring of changes over time. For example, many agricultural LTES have multiple plots of land, assigned management regimes varying in tillage, nutrient amendment, or crop rotation (Paul et al. 1997). Ideally, such LTES include a baseline treatment, against which prospective or extreme management regimes can be evaluated.

The fundamental purpose of an LTES is to monitor and understand the persistence of one or more ecosystems in delivering expected services. In the past, researchers, especially in studies of managed ecosystems, often focused on a system's continuing capacity to produce yield of food, timber, or other economic commodity. Increasingly, however, ecologists are interested also in other functions, such as maintaining biodiversity, filtering air and water, recycling wastes, sequestering atmospheric carbon, promoting aesthetic appeal, preserving recreational or cultural value, and sustaining soil health (Adhikari and Hartemink 2016; MEA 2005). By continuously or repeatedly measuring a system's capacity to furnish these services, either directly or using proxy indicators, researchers can determine whether an ecosystem's performance is improving, holding steady, or declining. In short, the purpose of LTES is to measure and understand the systems' resilience (Dudley 2011; Folke 2006; Folke et al. 2003; Holling 1973), although that term has now been used so widely, in so many ways, that its definition is becoming diluted (Downes et al. 2013; Hodgson et al. 2015).

The inherent value of LTES, of course, lies in their longevity. The most critical question, then, in defining an LTES is, what constitutes "long term"? How old does a study need to be before being designated an LTES? One way of resolving this question is to define an LTES prospectively, not retrospectively; to designate a site as an LTES not by time already elapsed but by lifespan intended. From this perspective, as proposed here, an LTES is a study site conceived and maintained deliberately to outlive the tenure of its founders, a site explicitly envisioned to be passed along, as a bequest to future ecologists (Haughland et al. 2010). By this definition, an ecological site established 1 year ago in such a way that it might furnish useful findings to later generations would already be deemed an LTES; but a complex agronomic experiment that has survived 10 years is not, if its continuation is threatened by stifling resource demands. This multigenerational perspective reorients the design and management of the LTES to focus less on answering currently topical questions and more on the challenges confronting future scientists. Just as scientists now derive enormous insight from studies established by their predecessors, so too the primary benefit of LTES established today may reside in what their successors may learn from them. Given the uncertainty over coming biospheric changes (Sutherland 2013; Villa et al. 2014; Weinberger 2012) and the challenges emanating from them, LTES begun today will likely have their greatest value in answering questions no one has yet foreseen.

19.3 Attributes of Enduring Long-Term Ecological Sites

LTES are almost universally prized and revered among ecologists, yet many face abandonment, threatened by accumulating costs and perceived obsolescence. How can LTES be designed to increase likelihood of their survival over multiple generations?

One important attribute is elegant simplicity—creative parsimony. A design too complex demands too many resources, increasing risk of termination during inevitable budgetary crises (Koehler and Melecis 2010; Leigh et al. 1994). In experiments at Lethbridge, for example, many plots with innovative cropping systems were established in 1911, but few survived; and those that did were not always the ecologically favored, but often just the simplest (Janzen 1995, 2001). Aside from its frugality, simplicity also confers flexibility, because it allows the individual plots to be of sufficient scale for management regimes gradually to be adapted or subdivided over time, avoiding obsolescence (Powlson et al. 2014).

A second attribute, following upon the first, is to select management regimes that best illuminate the functioning of the ecosystems under study. The purpose of LTES is not to identify or demonstrate the "best" system from among a range of conceivable options but rather to help researchers understand how ecosystems respond to stresses and management practices. Such understanding sometimes emerges most clearly from extreme management regimes, which may not always be commercially feasible or recommended (Palmer 1949; Powers and Van Cleve 1991). Saunders (1900), for example, in referring to a "long-conducted and extensive series of tests" observed that "these experiments were never intended to serve as model test plots such as farmers could copy to advantage in their general practice. On the contrary, it has been found necessary to use some fertilizers in extravagant quantities, and in other instances to more or less exhaust the soil…." A long-term experiment in Sweden, similarly, included a bare fallow treatment, clearly not viable economically, yet instrumental in developing a robust soil carbon model (Andrén and Kätterer 1997). In the past, LTES have sometimes been terminated because their management regimes were considered "obsolete"—no longer recommended for adoption by land managers. If the intent of LTES, as proposed here, is to understand unfolding ecosystem responses over time, then their value is not determined by how up to date their treatments are, but by how much insight they generate about ecosystem performance.

Third, the scientific value of any LTES, and hence the likelihood of its survival, is enhanced by melding it deliberately into multisite networks. From early on, researchers saw that many sites, seen together, give broader, more durable insights than the same sites studied alone. For example, agricultural scientists in Canada realized a century ago the importance of linking LTES across geographical regions (Anonymous 1924). Studies at many sites across the Canadian prairies were jointly established, with some common management regimes, and a consistent initial sampling of soils (Janzen 2001). This same motive led to the creation of LTES networks, perhaps most prominently in the U.S. LTER (Callahan 1984), but later extended also to Europe and beyond (LTER Europe 2016; Smith et al. 2002; Vanderbilt et al. 2015). Such networks have yielded bountiful understanding, but challenges remain; for example, scientists sometimes exhibit justifiable reluctance in sharing unpublished data (Hampton et al. 2013; Peters et al. 2013). Another challenge is resolving inevitable inconsistencies in research methods. For example, although soil carbon is widely measured in LTES, researchers do not always agree on uniform ways of sampling soils, of analyzing them, or even of expressing their carbon content (Jandl et al. 2014). Consequently, although progress in forging long-term research networks has been admirable (e.g., Richter et al. 2011), opportunity still remains to further enhance synergy among the LTES worldwide.

A further characteristic of enduring LTES is their integration with other research approaches. One reason that LTES sometimes falter is their slow delivery of findings, and the condescending perception that they amount to “mere monitoring,” not innovative, hypothesis-driven research (Keeling 2008; Taylor 1989). Funding agencies are not always generous with studies promising answers decades away (Callahan 1984; Müller et al. 2010; Risser 1991). And researchers too may be reluctant to invest in LTES because such studies do not always produce many publications quickly (Anonymous 2007; Nisbet 2007). As articulated already a century ago (Allen 1922), this difficulty can be assuaged by linking LTES with process-level studies. In this way, the LTES become the birthplace of new hypotheses (and burial grounds for old ones), in an endless iterative cycle: the LTES spawn new enigmas, which are addressed in process-level studies, yielding hypotheses evaluated in the LTES, which invariably generate new questions (Figure 19.2) (O’Gorman and Woodward 2013). Long-term experiments at Lethbridge, for example, revealed an inexplicable imbalance in long-term nitrogen budgets, as seen also in other long-term experiments, prompting studies of N_2 fixation and N deposition, still ongoing (Bremer et al. 1995; McGinn et al. 2003). In the same way, LTES are also indispensable in the building and testing of models (Loveland et al. 2014; Nisbet et al. 2014; Pielou 1981). For example, a model might mimic nicely the changes in soil carbon but falter in tracing signals of radiocarbon measured in LTES (Ellert and Janzen 2006), thus keeping scientists properly humble and advancing further inquiry. LTES, then, can be seen as a connective, synthesizing venue of research, weaving together strands of science across dimensions of time and space, thereby enticing researchers (and maybe also funding agencies) (Figures 19.1 and 19.2). Acclaimed new findings in ecological science, often enough, are indebted to insights quietly gleaned from LTES without them always being recognized.

Another attribute of enduring LTES is the consistent archiving of records, data, and samples for use at a later time. The impressive archives at

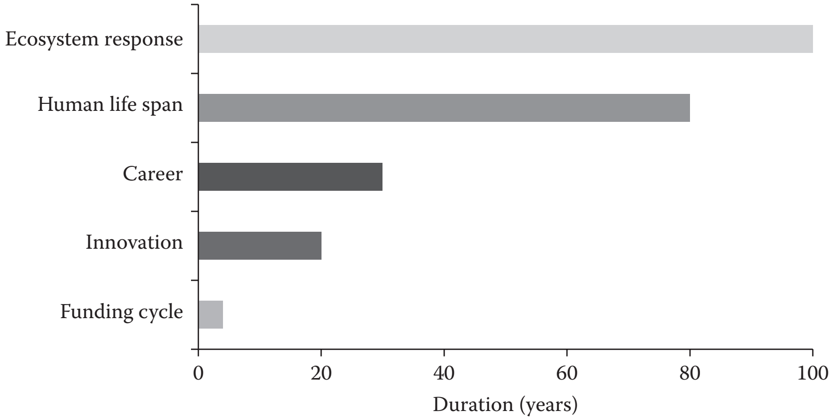

FIGURE 19.1
The duration of ecosystem response to management change or environmental upheaval, compared to that of a typical funding cycle, technological innovation, human career, and human lifespan. (From Kümmerer, K. et al., *J. Soil Water Conserv.*, 65, 141, 2010, based on Figure 1.)

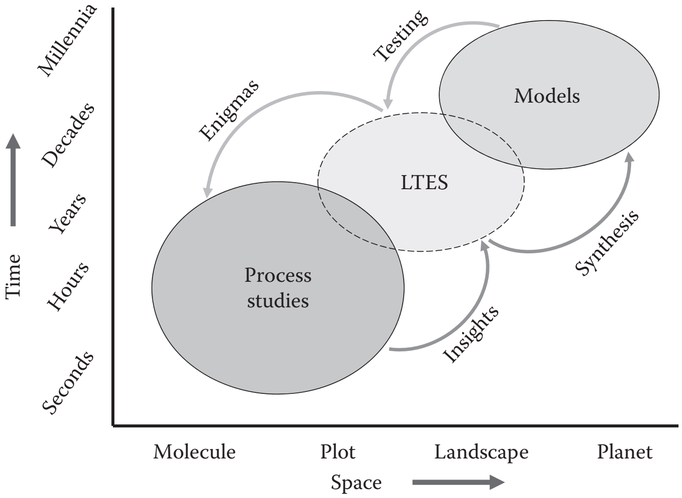

FIGURE 19.2
LTES as integrative elements in studies of ecosystem change. LTES generate questions (enigmas) that are addressed in process-level studies. Insights arising from such fundamental studies are evaluated over the long term in LTES, and findings are synthesized into ecosystem models. These models are evaluated over time in continuing LTES, invariably eliciting new enigmas, continuing the cycle. (Adapted from Janzen, H.H., *Glob. Chang. Biol.*, 15, 2770, 2009, Figure 3.)

Rothamsted, for example, are now as valuable as the experiments themselves (Leigh et al. 1994; Powlson et al. 2014). Long-term experiments maintained by INRA similarly have extensive archives of soils (van Oort 2013). Archived samples from these and other LTES serve as a repository for future analyses that those who collected the samples could not possibly have foreseen. For example, soil samples collected from Broadbalk, Rothamsted, in 1886 were used for innovative radiocarbon analysis a century later (Jenkinson et al. 1994). A challenge for LTES experimenters now is to decide what types of samples should be preserved for future scientists. For example, aside from collecting soil samples, experimenters may also want to consider storing samples of water, plant tissues, animal tissues, and DNA of plants, animals, and microbes. By far-sighted storage of samples from LTES, their value to science may continue even after the studies themselves have long expired.

Not all existing LTES should necessarily be continued indefinitely. Sometimes, the credibility of their findings is irretrievably compromised by flawed design, lapses in continuity, or disturbances such as urban encroachment. In other instances, the ecosystem under study is already adequately studied at other sites, resulting in unmerited duplication. Under such circumstances, terminating selected sites may help shift finite resources toward new or other ongoing studies. Always, however, LTES should be discontinued only after thorough, sober review; for example, scientists might have lost a treasured LTES if Lawes and Gilbert had not understood and vigorously defended the future value of Rothamsted experiments in the late nineteenth century (Johnston 1994).

19.4 New Directions

Existing LTES provide indispensable understanding of ecosystem response to human management and other drivers of global change. But the current slate of studies has gaps that may merit new or redirected LTES. Perhaps the most urgent is the establishment of more such studies in developing countries, where stresses on ecosystems are often most intense, lands are most vulnerable to global changes, and current LTES are most sparse (Fankhauser and McDermott 2014; Greenland 1994; Wheeler and von Braun 2013). Further, more LTES may be needed in urban lands, where most people now live and human stresses are often most pronounced (Pearson 2013; Vasenev et al. 2013). Although ecologists have sometimes shied away from studying such "novel" ecosystems, urban lands occupy increasing areas and can offer many services and potential opportunities for renewal (Ellis 2011; Lovell and Johnston 2009). More LTES are also required to monitor changes in polar ecosystems, where changes to climate may be more rapid and extreme than elsewhere (O'Gorman and Woodward 2013). Because these ecosystems may contain as much as one half of the global organic carbon stored belowground (Tarnocai et al. 2009), impending changes may induce substantial feedbacks to the global carbon cycles (Schaefer et al. 2011; Schuur et al. 2008; Tarnocai et al. 2009). Finally, more LTES may be justified on the vast areas of ecosystems already degraded by human activity (Smith et al. 2010). In the past, many ecological studies have focused, justifiably, on conserving ecosystems and avoiding degradation. But scientists are increasingly aware that ecosystems, once degraded, often demonstrate gradual recovery, if studied over long enough time periods (Jones and Schmitz 2009; Kareiva and Marvier 2012; Nelder 2013). For example, a soil stripped of its topsoil was shown in an LTES to slowly recover productivity and soil health over periods of decades, even without vigorous reclamation measures (Larney et al. 2016). The preceding are just a few examples of apparent gaps in the current suite of LTES. What is needed is a broad spectrum of such studies, distributed across the biomes, beyond the frequent focus on ecosystems with immediate economic returns.

A further challenge, aside from establishing LTES in new geographical locations, is devising new designs and approaches. A particular limitation of many current LTES is their small scale. Some important ecosystem services such as providing wildlife habitat, ensuring biodiversity, and filtering water can be properly studied only at landscape or larger scales (Francis et al. 2014; Godfray and Garnett 2014; Tscharntke et al. 2012; Wiens 2013), areas not easily encompassed in a typical LTES (Powlson et al. 2014). Possible approaches to resolve this difficulty include using “spatially nested” configurations (Syrbe et al. 2010) or establishing scaled-down ecosystems such as “farmlets” (Eisler 2014). With the growing scarcity of available land, every ecosystem will need to support multiple services concurrently (DeFries et al. 2012; Dosskey et al. 2012; Midgley 2012; Poppy et al. 2014). If, as proposed in this review, the intent of LTES is to study ecosystems’ continuing capacity to furnish these services, then creative ingenuity will be required to envision new designs that broaden the range of services studied.

Another recent development, meriting stronger consideration in LTES, is the study of social-ecological systems (Cumming et al. 2012; Gragson 2013; Haberl et al. 2006; Mauz et al. 2012; Singh et al. 2013). Now, in the Anthropocene, humans are often the primary drivers of change in ecosystems (Barnosky et al. 2012; Crutzen and Stoermer 2000; Ellis 2011; Kareiva and Marvier 2012). At the same time, humans depend on land as much as ever and hence are vulnerable to changes in ecosystems over time. For example, soil degradation in ecosystems affects not only food supply but also human poverty and political stability (Lal 2008). One way of including human influences and dependencies may be the coupling of LTES with life-cycle analysis. Consider, for example, systems for producing livestock, now the largest anthropogenic user of land (Cassidy et al. 2013) and a source of both environmental harm and benefit (Eisler 2014; Franzluebbers et al. 2012; Janzen 2011; Pelletier et al. 2011; Smil 2013; Vinnari and Tapio 2012; Westhoek et al. 2014). Researchers have begun to use life-cycle analysis to evaluate the overall, system-wide effect of such systems on concerns such as greenhouse gas production (Beauchemin et al. 2010, 2011), but what is often missing is the contribution of gradual, slowly unfolding processes like soil carbon change (Herrero et al. 2013; Smith 2014; Soussana and Lemaire 2014). Melding long-term findings from LTES into life-cycle analysis thus enhances the understanding of social-ecological systems, but it represents just one example of potentially new ways of including human behavior more directly into LTES.

19.5 Conclusion

LTES remain an indispensable research tool for understanding ecosystem responses to impending global changes. Many ecosystem responses to these global stresses occur slowly, episodically, or in complex temporal patterns and can therefore be captured only by monitoring ecosystems for several decades or longer. The critical importance of this research tool and the changing nature of stresses imposed on ecosystems, however, may warrant some innovations in how and where such studies are conducted to ensure all vulnerable ecosystems are properly represented to broaden the measurements recorded and to devise innovative new approaches. A particular challenge will be including more explicitly the human dimension in social-ecological systems, now dominant on many lands.

Aside from improving and expanding LTES, scientists may also need to communicate more effectively the importance of such studies in ecological research. Many process-level studies and modelling efforts, at the forefront of research, are deeply dependent on findings and insights from LTES, but scientists have not always adequately highlighted this indebtedness. By communicating more explicitly the fundamental role of long-term studies to advancements in ecosystem research, today's scientists can help ensure that these priceless treasures survive and are bequeathed without compromise to future generations of scientists.

References

Adhikari, K. and A.E. Hartemink. 2016. Linking soils to ecosystem services—A global review. *Geoderma* 262:101–111.

Allen, E.W. 1922. The method of science in agriculture. *Scientific Agriculture* 2:181–185.

Andrén, O. and T. Kätterer. 1997. ICBM: The introductory carbon balance model for exploration of soil carbon balances. *Ecological Applications* 7:1226–1236.

Anonymous. 1924. *The Organization Achievements and Present Work of the Experimental Farms*. Ottawa, Ontario, Canada: Government Printing Bureau.

Anonymous. 2007. Patching together a world view. *Nature* 450:761.

Barnosky, A.D., E.A. Hadley, J. Bascompte et al. 2012. Approaching a state shift in Earth's biosphere. *Nature* 486:52–58.

Beauchemin, K.A., H.H. Janzen, S.M. Little, T.A. McAllister, and S.M. McGinn. 2010. Life cycle assessment of greenhouse gas emissions from beef production in western Canada: A case study. *Agricultural Systems* 103:371–379.

Beauchemin, K.A., H.H. Janzen, S.M. Little, T.A. McAllister, and S.M. McGinn. 2011. Mitigation of greenhouse gas emissions from beef production in western Canada—Evaluation using farm-based life cycle assessment. *Animal Feed Science and Technology* 166–167:663–677.

Boyd, I.L. 2012. The art of ecological modeling. *Science* 337:306–307.

Bremer, E., H.H. Janzen, and C. Gilbertson. 1995. Evidence against associative N_2 fixation as a significant N source in long-term wheat plots. *Plant and Soil* 175:13–19.

Callahan, J.T. 1984. Long-term ecological research. *Bioscience* 34 (1984):363–367.

Carpenter, S.R. 2002. Ecological futures: Building an ecology of the long now. *Ecology* 83:2069–2083.

Carpenter, S.R., H.A. Mooney, and J. Agard. 2009. Science for managing ecosystem services: Beyond the Millennium Ecosystem Assessment. *Proceedings of the National Academy of Sciences of the United States of America* 106:1305–1312.

Cassidy, E.S., P.C. West, J.S. Gerber, and J.A. Foley. 2013. Redefining agricultural yields: From tonnes to people nourished per hectare. *Environmental Research Letters* 8:034015.

Chapin, F.S., C. Folke, and G.P. Kofinas. 2009. A framework for understanding change. In *Principles of Ecosystem Stewardship. Resilience-Based Natural Resource Management in a Changing World*, eds. F.S. Chapin, G.P. Kofinas, and C. Folke, pp. 3–28. New York: Springer.

Collins, S.L. and D.L. Childers. 2014. Long-term ecological research and network-level science. *EOS, Transactions American Geophysical Union* 95:293–304.

Crutzen, P.J. and E.F. Stoermer. 2000. The anthropocene. *Global Change Newsletter* May 2000:41.

Cumming, G., P. Olsson, F. Chapin, and C. Holling. 2012. Resilience, experimentation, and scale mismatches in social-ecological landscapes. *Landscape Ecology.* 2012:1–12.

DeFries, R.S., E.C. Ellis, F.S. Chapin et al. 2012. Planetary opportunities: A social contract for global change science to contribute to a sustainable future. *Bioscience* 62:603–606.

Dosskey, M., G. Wells, G. Bentrup, and D. Wallace. 2012. Enhancing ecosystem services: Designing for multifunctionality. *Journal of Soil and Water Conservation* 67:37A–41A.

Downes, B., F. Miller, J. Barnett et al. 2013. How do we know about resilience? An analysis of empirical research on resilience, and implications for interdisciplinary praxis. *Environmental Research Letters* 8:1–8.

Dudley, N. 2011. *Authenticity in Nature. Making Choices about the Naturalness of Ecosystems*. New York: Earthscan.

Eisler, M.C. 2014. Agriculture: Steps to sustainable livestock. *Nature* 507:32–34.

Ellert, B. and H.H. Janzen. 2006. Long-term biochemical cycling in agroecosystems inferred from ^{13}C, ^{14}C, and ^{15}N. *Journal of Geochemical Exploration* 88:198–201.

Ellert, B.H., H.H. Janzen, and B.G. McConkey. 2000. Measuring and comparing soil carbon storage. In *Assessment Methods for Soil Carbon*, eds. J.M. Kimble, R.F. Follett, and B.A. Stewart, pp. 131–146. Boca Raton, FL: CRC Press.

Ellis, E.C. 2011. Anthropogenic transformation of the terrestrial biosphere. *Philosophical Transactions of the Royal Society A* 369:1010–1035.

Fankhauser, S. and T.K.J. McDermott. 2014. Understanding the adaptation deficit: Why are poor countries more vulnerable to climate events than rich countries? *Global Environmental Change* 27:9–18.

Folke, C. 2006. Resilience: The emergence of a perspective for social-ecological systems analyses. *Global Environmental Change* 16:253–267.

Folke, C., J. Colding, and B. Fikret. 2003. Synthesis: Building resilience and adaptive capacity in socio-ecological systems. In *Navigating Socio-Ecological Systems: Building Resilience for Complexity and Change*, eds. F. Berkes, J. Colding, and C. Folke, pp. 352–387. Cambridge, U.K.: Cambridge University Press.

Francis, C., J. Van Wart, and B. Johnson. 2014. How to regenerate rural community and ecoservices: Reversing the tragedy of the commons. *Agronomy Journal* 106:95–99.

Franklin, J.F. 1989. Importance and justification of long-term studies in ecology. In *Long-Term Studies in Ecology: Approaches and Alternatives*, ed. G.E. Likens, pp. 3–19. New York: Springer-Verlag.

Franzluebbers, A.J., L.K. Paine, J.R. Winsten et al. 2012. Well-managed grazing systems: A forgotten hero of conservation. *Journal of Soil and Water Conservation* 67:100A–104A.

Godfray, H.C.J. and T. Garnett. 2014. Food security and sustainable intensification. *Philosophical Transactions of the Royal Society B* 369:1–10.

Gragson, T.L. 2013. The contribution of anthropology to concepts guiding LTSER research. In *Long Term Socio-Ecological Research: Studies in Society-Nature Interactions Across Spatial and Temporal Scales*, eds. J.S. Singh, H. Haberl, M. Chertow, M. Mirtl, and M. Schmid, pp. 189–214. Dordrecht, the Netherlands: Springer.

Greenfieldboyce, N. 2012. Experiments that keep going and going and going. Long term science: When research outlives the researcher. http://www.npr.org/2012/11/23/165030844/experiments-that-keep-going-and-going-and-going (accessed March 2, 2016).

Greenland, D.J. 1994. Long-term cropping experiments in developing countries: The need, the history and the future. In *Long-Term Experiments in Agricultural and Ecological Sciences*, eds. R.A. Leigh and A.E. Johnston, pp. 187–209. Wallingford, CT: CAB International.

Grove, J.M., S.T.A. Pickett, A. Whitmer, and M.L. Cadenasso. 2013. Building an urban PTSER: The case of the Baltimore ecosystem study and the D.C./B/.ULTRA-Ex Project. In *Long Term Socio-Ecological Research: Studies in Society-Nature Interactions Across Spatial and Temporal Scales*, eds. J.S. Singh, H. Haberl, M. Chertow, M. Mirtl, and M. Schmid, pp. 369–408. Dordrecht, the Netherlands: Springer.

Gunderson, L. and C. Folke. 2011. Resilience 2011: Leading transformational change. *Ecology and Society* 16:30.

Haberl, H., V. Winiwarter, K. Andersson et al. 2006. From LTER to LTSER: Conceptualizing the socioeconomic dimension of long-term socioecological research. *Ecology and Society* 11:article 13.

Hampton, S.E., C.A. Strasser, J.J. Tewksbury et al. 2013. Big data and the future of ecology. *Frontiers in Ecology and the Environment* 11:156–162.

Haughland, D.L., J.-M. Hero, J. Schieck et al. 2010. Planning forwards: Biodiversity research and monitoring systems for better management. *Trends in Ecology and Evolution* 25:199–200.

Herrero, M. et al. 2013. Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. *Proceedings of the National Academy of Sciences of the United States of America* 110:20888–20893.

Hodgson, D., J.L. McDonald and D.J. Hosken. 2015. What do you mean, 'resilient'? *Trends in Ecology & Evolution*30:503–506.

Holling, C.S. 1973. Resilience and stability of ecological systems. *Annual Review of Ecology, Evolution and Systematics* 4:1–23.

ILTER. 2016. International long-term ecological research. http://www.ilternet.edu/ (accessed March 2, 2016) .

Jandl, R., M. Rodeghiero, C. Martinez et al. 2014. Current status, uncertainty and future needs in soil organic carbon monitoring. *Science of the Total Environment* 468–469:376–383.

Janzen, H.H. 1995. The role of long-term sites in agroecological research: A case study. *Canadian Journal of Soil Science* 75:123–133.

Janzen, H.H. 2001. Soil Science on the Canadian prairies—Peering into the future from a century ago. *Canadian Journal of Soil Science* 81:489–503.

Janzen, H.H. 2009. Long-term ecological sites: Musings on the future, as seen (dimly) from the past. *Global Change Biology* 15:2770–2778.

Janzen, H.H. 2011. What place for livestock on a re-greening earth? *Animal Feed Science and Technology* 166–167:783–796.

Jenkinson, D.S., N.J. Bradbury, and K. Coleman. 1994. How the Rothamsted classical experiments have been used to develop and test models for the turnover of carbon and nitrogen in soil. In *Long-Term Experiments in Agricultural and Ecological Sciences*, eds. R.A. Leigh and A.E. Johnston, pp. 117–138. Wallingford, CT: CAB International.

Johnston, A.E. 1994. The Rothamsted classical experiments. In *Long-Term Experiments in Agricultural and Ecological Sciences*, eds. R.A. Leigh and A.E. Johnston, pp. 9–37. Wallingford, CT: CAB International.

Jones, H.P. and O.J. Schmitz. 2009. Rapid recovery of damaged ecosystems. *PLoS ONE* 4:e5653.

Kareiva, P. and M. Marvier. 2012. What is conservation science? *Bioscience* 62:962–969.

Keeling, R.F. 2008. Recording earth's vital signs. *Science* 319:1771–1772.

Knapp, A.K., M.D. Smith, S.E. Hobbie et al. 2012. Past, present, and future roles of long-term experiments in the LTER network. *Bioscience* 62:377–389.

Koehler, H. and V. Melecis. 2010. Long-term observations of soil mesofauna. In *Long-Term Ecological Research: Between Theory and Application*, eds. F. Müller, C. Baessler, H. Schubert, and S. Klotz, pp. 203–220. Dordrecht, the Netherlands: Springer.

Kümmerer, K., M. Held, and D. Pimentel. 2010. Sustainable use of soils and time. *Journal of Soil and Water Conservation* 65:141–149.

Lal, R. 2008. Food insecurity's dirty secret. *Science* 322:673–674.

Larney, F.J., L. Li, H.H. Janzen, D.A. Angers, and B.M. Olson. 2016. Soil quality attributes, soil resilience and legacy effects following topsoil removal and one-time amendments. *Canadian Journal of Soil Science* 96:177–190.

Le Quéré, C., R. Moriarty, R.M. Andrew et al. 2015. Global carbon budget 2015. *Earth System Science Data* 7:349–396.

Leigh, R.A., R.D. Prew, and A.E. Johnston. 1994. The management of long-term agricultural field experiments: Procedures and policies evolved from the Rothamsted classical experiments. In *Long-Term Experiments in Agricultural and Ecological Sciences*, eds. R.A. Leigh and A.E. Johnston, pp. 253–268. Wallingford, CT: CAB International.

Loveland, P.J., F. Conen, and B. Van Wesemael. 2014. Batjes, N.H. 1996. Total carbon and nitrogen in the soils of the world. *European Journal of Soil Science* 47:151–163. Commentary on the impact of Batjes (1996). *European Journal of Soil Science* 65:4–21.

Lovell, S.T. and D.M. Johnston. 2009. Designing landscapes for performance based on emerging principles in landscape ecology. *Ecology Society* 14:article 44.

LTER Europe. 2016. Long-term ecosystem research in Europe http://www.lter-europe.net/ (accessed March 2, 2016).

Marsh, G.P. 1864. *Man and Nature; or, Physical Geography as Modified by Human Action*. New York: Charles Scribner.

Mauz, I., T. Peltola, C. Granjou et al. 2012. How scientific visions matter: Insights from three long-term socio-ecological research (LTSER) platforms under construction in Europe. *Environmental Science and Policy* 19–20:90–99.

McGinn, S.M., H.H. Janzen, and T. Coates. 2003. Atmospheric ammonia, volatile fatty acids, and other odorants near beef feedlots. *Journal of Environmental Quality* 32:1173–1182.

MEA (Millennium Ecosystem Assessment). 2005. *Ecosystems and Human Well-Being: Synthesis*. Washington, DC: Island Press.

Midgley, G.F. 2012. Biodiversity and ecosystem function. *Science* 335:174–175.

Mooney, H., A. Larigauderie, M. Cesario et al. 2009. Biodiversity, climate change, and ecosystem services. *Current Opinion in Environmental Sustainability* 1:46–54.

Müller, F., A. Gnauck, K.-O. Wenkel, H. Schubert, and M. Bredemeier. 2010. Theoretical demands for long-term ecological research and the management of long-term data sets. In *Long-Term Ecological Research: Between Theory and Application*, eds. F. Müller, C. Baessler, H. Schubert, and S. Klotz, pp. 11–25. Dordrecht, the Netherlands: Springer.

Nelder, C. 2013. Communication: Positive energy. *Nature* 498:293–295.

Nisbet, E.G. 2007. Earth monitoring: Cinderella science. *Nature* 450:789–790.

Nisbet, E.G., E.J. Dlugokencky, and P. Bousquet. 2014. Methane on the rise—Again. *Science* 343:493–495.

O'Gorman, E.J. and G. Woodward. 2013. Editorial commentary: Monitoring, manipulation and modelling of ecological responses to global change in multispecies systems. *Advances in Ecological Research* 48:xiii–xxii.

Palmer, A.E. 1949. *Progress Report 1936–1946 Dominion Experimental Station, Lethbridge, Alberta*. Ottawa, Ontario, Canada: Government of Canada.

Paul, E.A., K.H. Paustian, E.T. Elliott, and C.V. Cole. 1997. *Soil Organic Matter in Temperate Agroecosystems: Long Term Experiments in North America*. Boca Raton, FL: CRC Press.

Pearson, L.J. 2013. In search of resilient and sustainable cities: Prefatory remarks. *Ecological Economics* 86:222–223.

Pelletier, N., E. Audsley, S. Brodt et al. 2011. Energy intensity of agriculture and food systems. *Annual Review of Environmental Resources* 36:223–46.

Peters, D.P.C., C.M. Laney, A.E. Lugo et al. 2013. Long-term trends in ecological systems: An introduction to cross-site comparisons and relevance to global change studies. In *Long-Term Trends in Ecological Systems: A Basis for Understanding Responses to Global Change*, eds. D.P.C. Peters, C.M. Laney, A.E. Lugo et al., pp. 1–20. Las Cruces, NM: USDA Agricultural Research Service Department of Agriculture Technical Bulletin No. 1931.

Pielou, E.C. 1981. The usefulness of ecological models: A stock-taking. *Quarterly Review of Biology* 56:17–31.

Poppy, G.M., S. Chiotha, F. Eigenbrod et al. 2014. Food security in a perfect storm: Using the ecosystem services framework to increase understanding. *Philosophical Transactions of the Royal Society B* 369:1–13.

Powers, R.F. and K. Van Cleve. 1991. Long-term ecological research in temperate and boreal forest ecosystems. *Agronomy Journal* 83:11–24.

Powlson, D.S., A.J. MacDonald, and P.R. Poulton. 2014. The continuing value of long-term field experiments: Insights for achieving food security and environmental integrity. In *Soil as World Heritage*, ed. D. Dent, pp. 131–157. Dordrecht, the Netherlands: Springer.

Richter, D., A.R. Bacon, M. Mobley et al. 2011. Human-soil relations are changing rapidly: Proposals from SSSA's Cross-Divisional Soil Change Working Group. *Soil Science Society of America Journal* 75:2079–2084.

Richter, D., D. Holfmockel, M.A. Callaham, D.S. Powlson, and P. Smith. 2007. Long-term soil experiments: Keys to managing earth's rapidly changing ecosystems. *Soil Science Society of America Journal* 71:266–279.

Risser, P.G. 1991. Introduction. In *Long Term Ecological Research. An International Perspective*, ed. P.G. Risser, pp. 1–8. Chichester, U.K.: John Wiley & Sons Ltd.

Saunders, W. 1900. Annual report of the experimental farms. In *Appendix to the Report of the Minister of Agriculture,* ed. S.E. Dawson, pp. 5–66. Ottawa, Canada.

Schaefer, K., T. Zhang, L. Bruhwiler, and A.P. Barrett. 2011. Amount and timing of permafrost carbon release in response to climate warming. *Tellus B.* 63:165–180.

Schuur, E.A.G., J. Bockheim, J.G. Canadell, E. Euskirchen, C.B. Field, S.V. Goryachkin, et al. 2008. Vulnerability of permafrost carbon to climate change: Implications for the global carbon cycle. *BioScience* 58:701–714.

Singh, J.S., H. Haberl, M. Chertow, M. Mirtl, and M. Schmid. 2013. Introduction. In *Long Term Socio-Ecological Research. Studies in Society: Nature Interactions Across Spatial and Temporal Scales*, eds. J.S. Singh, H. Haberl, M. Chertow, M. Mirtl, and M. Schmid, pp. 1–26. Dordrecht, the Netherlands: Springer.

Smil, V. 2013. *Should We Eat Meat? Evolution and Consequences of Modern Carnivory.* Chichester, U.K.: Wiley-Blackwell.

Smith, P. 2014. Do grasslands act as a perpetual sink for carbon? *Global Change Biology* 20:2708–2711.

Smith, P., P.D. Falloon, M. Korschens et al. 2002. EuroSOMNET—A European database of long-term experiments on soil organic matter: The WWW metadatabase. *Journal of Agricultural Science* 138:123–134.

Smith, P., P.J. Gregory, D. van Vuuren et al. 2010. Competition for land. *Philosophical Transactions of the Royal Society B* 365:2941–2957.

Soussana, J.-F. and G. Lemaire. 2014. Coupling carbon and nitrogen cycles for environmentally sustainable intensification of grasslands and crop-livestock systems. *Agriculture, Ecosystems and Environment* 190:9–17.

Southwood, T.R.E. 1994. The importance of long-term experimentation. In *Long-Term Experiments in Agricultural and Ecological Sciences*, eds. R.A. Leigh and A.E. Johnston, pp. 3–8. Wallingford, CT: CAB International.

Sutherland, W.J. 2013. Policy: Twenty tips for interpreting scientific claims. *Nature* 503:335–337.

Syrbe, R.-U., W. Hierold, O. Bastian, and M. Roder. 2010. A conceptual framework for integrated functional landscape monitoring in the wider countryside of central Europe. In *Long-Term Ecological Research: Between Theory and Application*, eds. F. Müller, C. Baessler, H. Schubert, and S. Klotz, pp. 263–278. Dordrecht, the Netherlands: Springer.

Tansley, A.G. 1935. The use and abuse of vegetational concepts and terms. *Ecology* 16:284–307.

Tarnocai, C., J.G. Canadell, E.A.G. Schuur, P. Kuhry, G. Mazhitova, and S. Zimov. 2009. Soil organic carbon pools in the northern circumpolar permafrost region. *Global Biogeochemical Cycles* 23:GB2023.

Taylor, R.L. 1989. Objective and experiment in long term research. In *Long-Term Studies in Ecology: Approaches and Alternatives*, ed. G.E. Likens, pp. 20–70. New York: Springer-Verlag.

Telewski, F.W. and J.A.D. Zeevaart. 2002. The 120-yr period for Dr. Beal's seed viability experiment. *American Journal of Botany* 89:1285–1288.

Tingley, M.W. 2013. Ecosystems: Climate change must not blow conservation off course. *Nature* 500:271–272.

Tscharntke, T., Y. Clough, T.C. Wanger et al. 2012. Global food security, biodiversity conservation and the future of agricultural intensification. *Biology Conservation* 151:53–59.

van Oort, F. 2013. INRA's 42 plots design (Versailles, France) since 1928: A world's unique long-term bare fallow experiment. Grignon, Savoie, France: INRA, Centre de Versailles.

Vanderbilt, K.L., C.-C. Lin, S.-S. Lu et al. 2015. Fostering ecological data sharing: Collaborations in the International Long Term Ecological Research Network. *Ecosphere* 6: article 204.

Vasenev, V.I., J.J. Stoorvogel, and I.I. Vasenev. 2013. Urban soil organic carbon and its spatial heterogeneity in comparison with natural and agricultural areas in the Moscow region. *Catena* 107:96–102.

Villa, F., B. Voigt, and J.D. Erickson. 2014. New perspectives in ecosystem science to understand environmental securities. *Philosophical Transactions of the Royal Society B* 369:1–15.

Vinnari, M. and P. Tapio. 2012. Sustainability of diets: From concepts to governance. *Ecology Economics* 74:46–54.

Weinberger, D. 2012. To know, but not understand: David Weinberger on science and big data. *The Atlantic,* January 3, 2012. http://www.theatlantic.com/technology/archive/2012/01/to-know-but-not-understand-david-weinberger-on-science-and-big-data/250820/ (accessed October 24, 2016).

Westhoek, H., J.P. Lesschen, T. Rood et al. 2014. Food choices, health and environment: Effects of cutting Europe's meat and dairy intake. *Global Environmental Change* 26:196–205.

Wheeler, T. and J. von Braun. 2013. Climate change impacts on global food security. *Science* 341:508–513.

White, M.A. 2013. Sustainability: I know it when I see it. *Ecology Economics* 86:213–217.

Wiens, J. 2013. Is landscape sustainability a useful concept in a changing world? *Landscape Ecology* 28:1047–1052.

Willis, A.J. 1997. The ecosystem: An evolving concept viewed historically. *Functional Ecology* 11:268–271.