CHAPTER

19

Long-term forest soils research: lessons learned from the US experience

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ABSTRACT

Long-term research studies are critical to understanding soil productivity and the sustainability of forest and woodland ecosystems around the world. They inform management decisions about best harvest techniques, soil property impacts and recovery, anthropogenic stressors (e.g., forest management, acid rain, climate change), and the influence if governmental policies, guidelines, and regulations. Forest ecosystems represent a major source of drinking water in much of the world making the interaction of atmospheric chemistry, vegetation, land use, soil and water one of global importance. This intimate connection among interacting variables also make forests a logical system to study ecosystem processes. In this chapter we discuss the challenges and benefits of establishing and maintaining long-term studies, the utility of these studies for informing decisions about how to manage forest soil to sustain the delivery of ecosystem services and lessons learned for forest research.

Introduction

Long term research studies yield information about temporal changes in soil and soil's interactions with vegetation and the surrounding environment. Despite their value to understanding these changes and interactions, we have relied on remarkably few long-term field studies that directly observe time-dependent soil changes by repeated soil sampling. In an inventory of well over 200 long-term field studies world-wide, about 15% were studies of forest and rangeland soils (Yaalon, 2012). Significantly, what these foresighted field studies clearly demonstrate is that soil is highly responsive to management and that the soil system is dynamic on a decadal time scale (Mobley et al., 2015).

The concept of continuous soil change continues to be explored in a world with changing climate, increased frequency of insect and disease infestations, and changing vegetation communities due to agricultural use, land abandonment, and forest management, all things that make a static soil impossible. Polygenesis or continued evolution of soils incorporates this paradigm into the

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existing historical concepts of soil formation and soil taxonomy (Yaalon, 2012). Soils change under constant conditions or when they are exposed to new environmental conditions; rates of change vary with environmental conditions while changes to these rates are determined by the magnitude of changes in the environment. Some soil physical, chemical and biological reactions can respond to changes in conditions (e.g., fertilization or tillage) in a matter of seconds or days (<1 year). On the other extreme, parent material weathering, clay formation (>100 years) or podzolization can take much longer (1000–10,000 years) (Fig. 19.1) (Yaalon, 1990), although see Austin et al. (2018) for exceptions. This perspective on soil development acknowledges the need to study soil changes (i.e., soil C and nutrient pools, and soil processes) in response to climate, atmospheric inputs, vegetation composition, and microbial communities. Long-term research is essential to understanding soils as an integral part of the forest ecosystem as well as their past, current, and future role in sustaining ecosystem services. Soil scientists appreciate the fact that shorter term temporal changes do not generally over-ride the impact of the soil forming factors considered in Soil Taxonomy making mapped soil series a valuable tool for understanding temporal and spatial measurements of change.

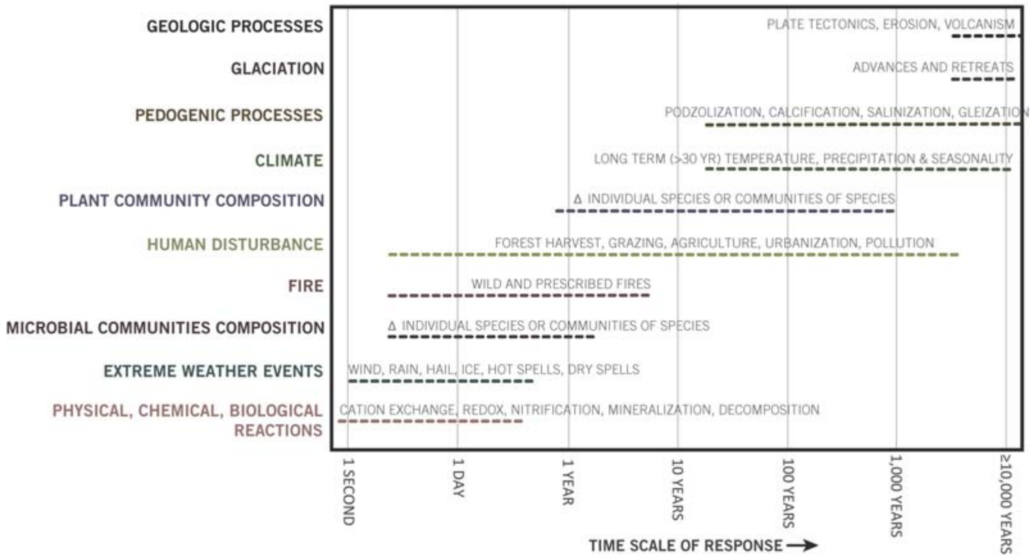


FIG. 19.1

Conceptual framework for understanding timescale of forest soil change. Rustad, L., J. D. Knoepp et al. (in press). Biogeochemical cycling in forest and rangeland soils of the United States. USDA Forest Service National Soil Assessment. T. Patel-Weynand. Washington DC, USDA Forest Service.

In this chapter we present an overview of long-term research in forest soils, specifically the important role of long-term research in understanding long-lived forest ecosystems. This research is supported by several international networks, which were established to conduct research on different aspects of forests but now represent sites with long-term measurements and will continue to add important information into the futures. Soils play a critical role in the function of forests, but because we could not cover all areas of research we focused on impacts of forest management, the role of acid rain research in understanding soil processes, soil fauna biodiversity, long-term research using the ecosystem approach and “ecological surprises”.

Research to understand the impacts of land use on soils

The importance of science in understanding the impacts of land use and management on forests was evident to scientists in the late 1800s and resulted in the submission of letters by the American Association for the Advancement of Science (in 1873) and the National Academy of Sciences (in 1896) seeking support for the establishment of the US Department of Agriculture (USDA) Forest Service (Williams, 2000). This was followed in 1902 by the establishment of a Section of Special Investigations (Research) to help meet the science needs of local forests (Williams, 2000). However, the use of scientific findings in the preparation of forest plans, which in part define forest priorities, has not always been brought into practice, as many management decisions on US National Forests remain political in nature. The 2012 Forest Planning Rule of the USDA Forest Service mandated the use of ‘the best available science’ to ensure that land management decisions are designed to yield desired outcomes based on scientific research. This effort was designed to improve management outcomes but also increase public support by making decisions that relied on scientifically collected data. Sound management based on rigorous science continues to be important today, yet there are often significant lag times between the identification of an issue, the completion and publication of research addressing the issue, and the implementation of those results into policy and practice (Likens, 2010). The often long periods of time being problem identification and implementation of solutions highlights why, long-term research is essential to solving today’s management issues. Collection of long-term data on forest systems, ecosystems often defined by their longevity, allows researchers to categorize patterns of resistance and/or resilience in response to change or disturbance.

Establishment of research networks

Efforts to facilitate long-term data collection, standardize methods, and provide increased spatial diversity of research have inspired the organization of a number of research networks. One of the earliest networks was the Experimental Forests and Ranges (EFR) created by the USDA Forest Service. The EFR network was established to examine the effects of land use and forest management practices applied across the U.S. and to support research on regionally specific forest management issues, and to evaluate and modify, where needed, forestry activities. The first EFR, Fort Valley, Flagstaff, AZ, was established in 1908 to study ponderosa pine (*Pinus ponderosa*) ecology and management. Many EFR sites followed, with 82 EFR still managed by the Forest Service today. The establishment of EFRs required a commitment to conduct meaningful long-term research and, while many experimental forests are still highly functional and productive, others sadly are not, due to lack of funding. Currently, all USDA Forest Service Research Stations have efforts underway to improve their contributing EFR network sites so they can enhance their capacity to continue to produce the published long-term data-sets required for understanding our changing world. There are still long-term data sets that are being produced and published (Table 19.1; Fig. 19.2).

Table 19.1 Forest soil publication history.

Search topic	First publication	–1979	1980–9	1990–9	2000–9	2010–8
Forest soils	1900	788	1084	10,934	25,110	49,305
Forest soils &						
Soil survey	1945	10	4	463	1109	2078
Silviculture	1928	1		55	151	279
Harvest or management	1930	5	22	1715	5256	10,421
Whole tree harvest	1986		3	102	155	494
Clear cut harvest	1977	3	16	248	540	616
Biomass or bioenergy	1973	9	20	2173	5278	9606
Acid rain (only)	1910	389	1499	8027	11,469	19,297
Forest soils &						
Acid rain	1980		27	843	879	929
Clean air Act	1958	86	614	2723	3057	3649
Chemistry	1925	24	51	2171	4184	6274
Carbon (organic matter)	1928	31	78	3527	10,610	20,025
Biodiversity	1967	1	3	964	3863	9418
Ecosystem	1969	13	45	3112	8463	16,544
Long term	1975	3	22	1252	3172	5521
Water quality/chemistry	1977	1	3	926	1956	2885
Climate change	1987		2	742	2693	8765

Citations identified in the Core Science Collection ofWeb of Science with date range 1900 through 2018.
Search terms included: Clean air act; acid rain (acid and rain) or acid precipitation. Forest soil (Forest and soil*) first term in all searches followed by and, *diversity; Fertiliz(s)ation; Silviculture; Water or stream and quality or chemistry; Harvest and Whole tree or whole-tree; Soil survey; Long and term or long-term; Acid and rain; Harvest, Clear cut or clearcut; Biomass or bioenergy.*

In 1957—58, the International Geophysical Year (IGY), scientific efforts to examine the interconnectedness of global environmental processes, including biological processes, brought about funding in 1963 for the International Biological Program (IBP) by countries across Europe, Asia, Canada and Commonwealth nations (Coleman, 2010). After the end of the IBP, the National Science Foundation (NSF) established the Long-term Ecological Research (LTER) program in 1980, led by many scientists previously funded by the IBP (Coleman, 2010). Several USDA Forest Service EFRs were incorporated into the LTER Network, and have been and continue to be important contributors to long-term research (Fig. 19.3). The need for a similar network of sites and increased collaboration between existing networks across the globe brought about the International LTER (ILTER) network in 1993. The ILTER has research on every continent and represents 700 sites and 200 institutions. Their long-term data sets represent over a century of ecological data. In the early 2000s, NSF funded the Research Coordination Network for Long-Term Soil-Ecosystem Experiments (RCN-LTSEs), which created the first

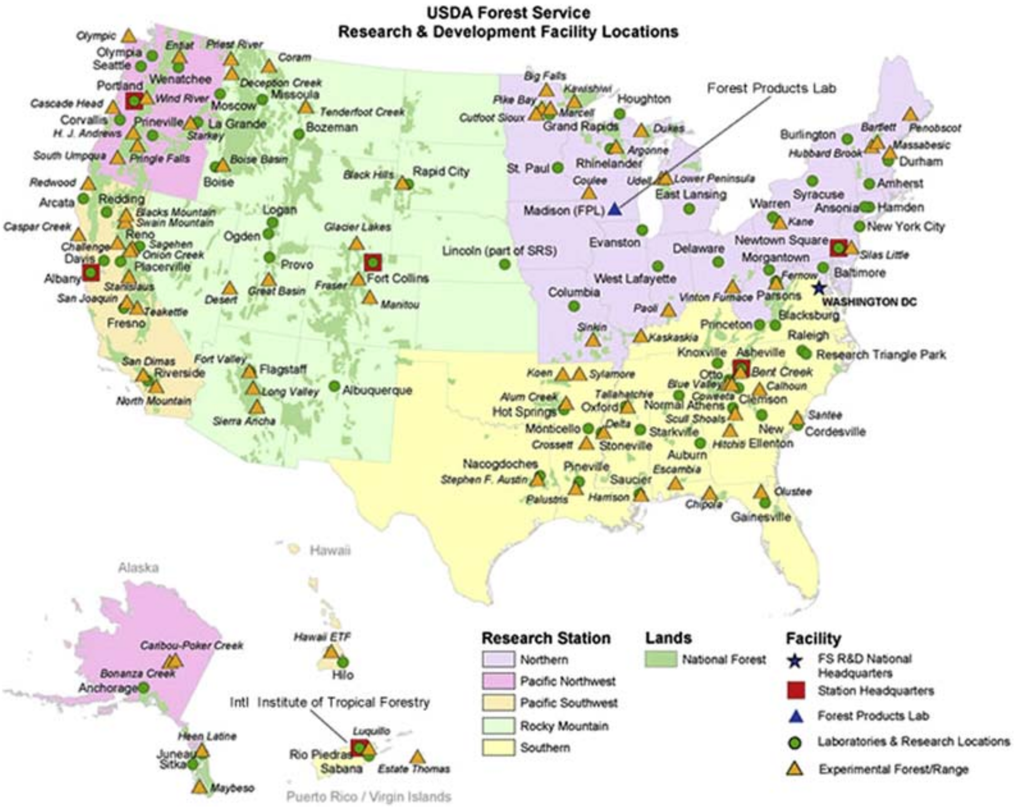


FIG. 19.2

Location of USDA Forest Service research facilities. Research and development. Washington DC. https://web.archive.org/web/20130903172616/http://www.fs.fed.us/research/locations/.

world-wide inventory and network of LTSEs. By 2010, more than 200 LTSEs had been inventoried, complete with metadata. Today, the data are hosted on a stable long-term website (http://iscn.fluxdata.org/partner-networks/long-term-soil-experiments-map/). The LTSEs are grouped in three tiers, prioritizing experiments with sample archives that span >40 years, 20–40 years, and < 20 years. The inventoried LTSEs represent a sample of the world's on-going soil experiments, but does not include all long-term studies (Richter and Markewitz, 2001).

The DIRT experiment

Soil organic matter is made up plant material inputs and can contain more than half the total organic C in a forest (Lal, 2005; Knoepp et al., 2018; Bowden et al. 2014). In 1956, Dr. Francis Hole and Gerald Nielson implemented a study of soil organic matter formation by altering above and below ground inputs (Nielson and Hole, 1963; Nadelhoffer et al., 2004). When asked how long he wanted his plots

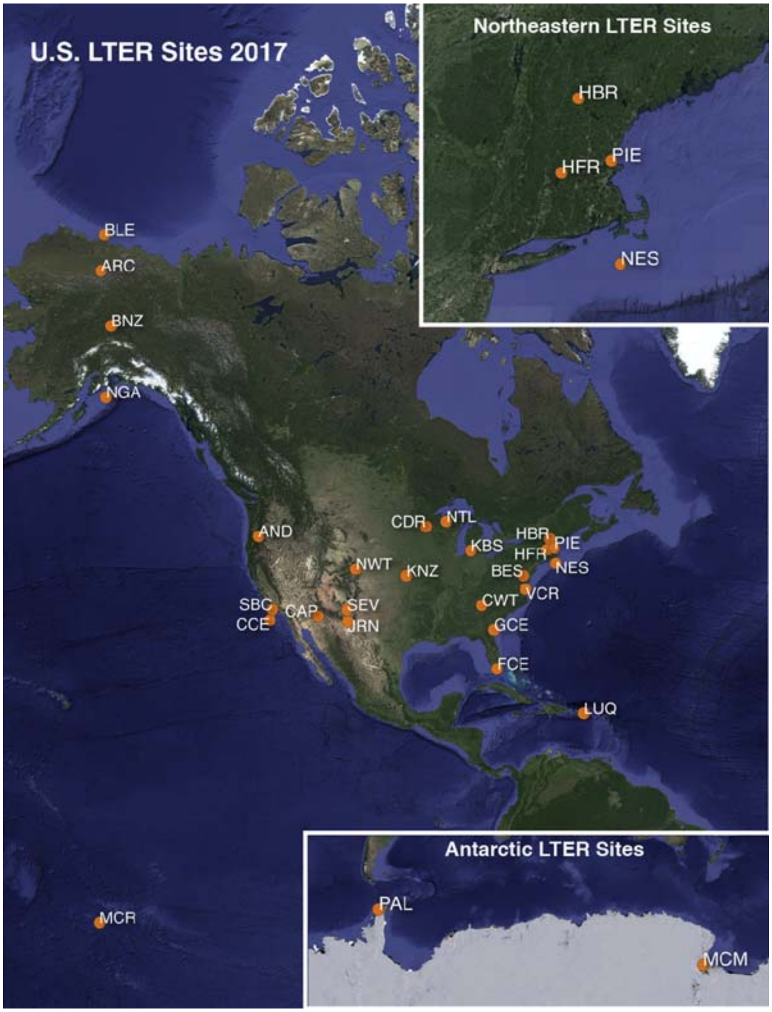


FIG. 19.3

Map showing location of National Science Foundation LTER sites.

maintained, Dr. Hole said, 'Oh, I'm hoping for a thousand years at least.' In 1984, 1997, Nadelhoffer et al. (2004) resampled these plots, naming the experiment 'detritus input and removal treatments' abbreviated DIRT. Between 1990 and 1997, the formation of a DIRT network began, with the installation of plots on 3 sites: (1) mixed oak (Harvard Forest, MA U.S.), (2) black cherry and sugar maple (Bousson Experimental Forest, PA U.S.) and (3) old growth Douglas-fir (H.J. Andrews Experimental Forest, OR US) (Lajtha et al., 2005; Nadelhoffer et al., 2004; Boone, 1994; Bowden et al., 1993). Soil sampling is infrequent to keep plot disturbance to a minimum and all collected soils are archived following measurements. Routine measurement of biological processes include soil enzyme activity (Lajtha et al., 2014), organic matter formation (Lajtha et al. 2018), and changes in molecular level chemistry of soil organic matter (Wang et al. 2017), as well as soil solution and gas fluxes. Between 1999 and 2013 additional sites across North America and Europe were installed (Lajtha et al. 2018; Fekete et al., 2014). The network of DIRT sites have yielded valuable information concerning the role of plant inputs in the formation of soil organic matter (Lajtha et al. 2018). Their work has shown a decline in soil organic matter pools when aboveground litter inputs are excluded, but little response when litter was doubled. Additionally, belowground (root) inputs did not play a significant role in soil organic matter stabilization compared to aboveground inputs. Their data also found that belowground contributions to soil respiration could be predicted using soil total C and N and that overall soil fertility was negatively related to the proportion of root respiration, and positively related to litter respiration.

All long-term study sites provide opportunities to test hypotheses about soil sustainability across a variety of land uses applied across contrasting soils, climates, landforms, and human cultures. To fully capitalize on the opportunities provided by these sites, there needs to be a corporate (global) commitment to data management and sample archiving for these long-term research sites, making data pertaining to soil chemical, physical, and biological properties open and accessible to the broader researcher community. These data could be used (e.g., meta-analyses) to test hypotheses about ecological processes and land management practices to provide insights into how to manage forest soils in the face of environmental change so that management and conservation can sustain the forest ecosystem services that are valuable to society.

Historical accounting of forest soils research

To highlight patterns and areas of focus in long-term forest soils research we searched the Web of Science Core Science Collection for the publication patterns of forest (forests, forestry) and soil (soils) across multiple research areas to illustrate changes in interest over time (Table 19.1) and how these shifts varied globally (Fig. 19.4). We certainly recognize that many early publications are not retrievable via electronic searches and while the Web of Science search includes documents dating back to 1900, this type of literature analysis is disproportionately weighted to more recent literature. Additionally, we must note that country of origin is not always indicated, especially in early publications and Web of Science limits the identification of countries of origin to 100. However, we believe this search provides a reasonable sampling of the temporal and spatial patterns resulting from the research and publication history in forested areas of the Earth. Following the forest soils search, we conducted additive searches with terms reflecting research areas that resulted in significant advances in our understanding of forest soils. We narrowed the focus of this chapter to focus on long-term forest soils research and included detailed discussion of silviculture, acidic deposition (with and without forest soil), biodiversity, and ecosystem science.

Forest soils research: general

The first occurrence on the topic forest soil (forest* and soil*) was in 1900 and by 1949 there were 88 publications with numbers increasing from ~1000 in the 1980s to >49,000 in 2010−8. While we find discussions of the identification of forest soils in early soil surveys (see Chapter 1 in this volume), this

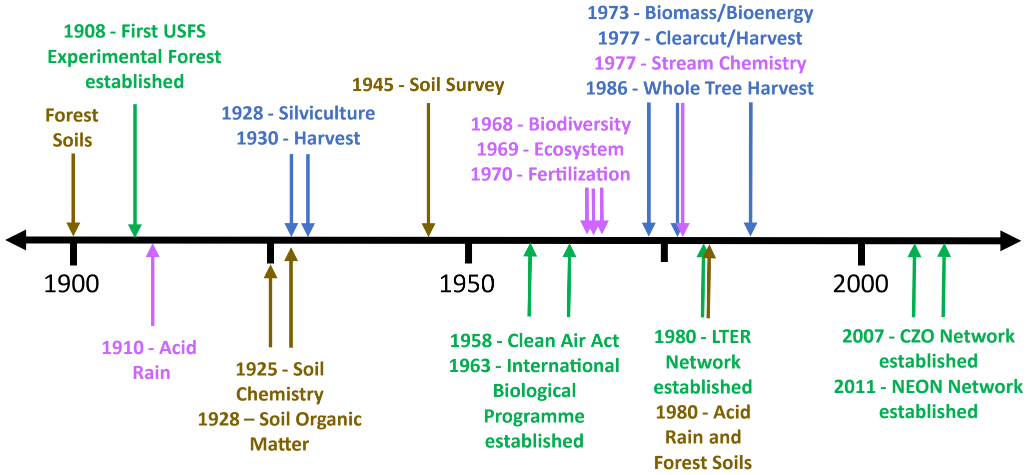


FIG. 19.4

Timeline showing dates of important events relating to forest soils. (Note: data is limited to literature published after 1900).

term is not associated with forest soils in our literature search until 1945. The origins of this research changed through time (Fig. 19.5A). The earliest publications (1900—49) came from the United States (US), Sweden and New Zealand, but, as noted above, for many publications the country of origin was not identified. From 1949 to 79 the number of countries with forest soil research increased to 44; the US, USSR, Canada and Federal Republic of Germany had the greatest number of publications. By 2000—18, 100 countries are listed with forest soil research and represent 6 continents. The US remained the most prolific publisher, followed by Peoples Republic of China, Germany, Brazil and Canada.

Forest soils research: forest management

More specifically, we examined patterns of research investigating the impacts of forest management on soils with a search that included both ‘forest soil’ and ‘silvic*’ (silvics, silviculture, etc.). These topics begin in 1928 but the number remained low through to the present at ∼200 from 2010—18 (Table 19.1). Publications that include more specific forest management practices are more numerous. Inclusion of ‘whole tree harvest’ began in 1986 with the most recent (2010—18) publication number of ∼500; ‘clear cut harvest’ begins in 1977 with a similar number of recent publications (>600). When the more general topic of ‘bioenergy or biomass’ was included, the number of published studies increased from 29 during the period of 1973—1989 to almost 10,000 in 2010—18, showing that harvest (biomass) removal remains a topic of worldwide interest. The global distribution of these publications confirms a broad interest in forest soils and forest management. During 1928—1979, publications primarily came from two countries Australia and US (Fig. 19.5B). As time progressed, the number of countries increased to eight (1979—89), but the US, Canada, and Australia remained the top three.

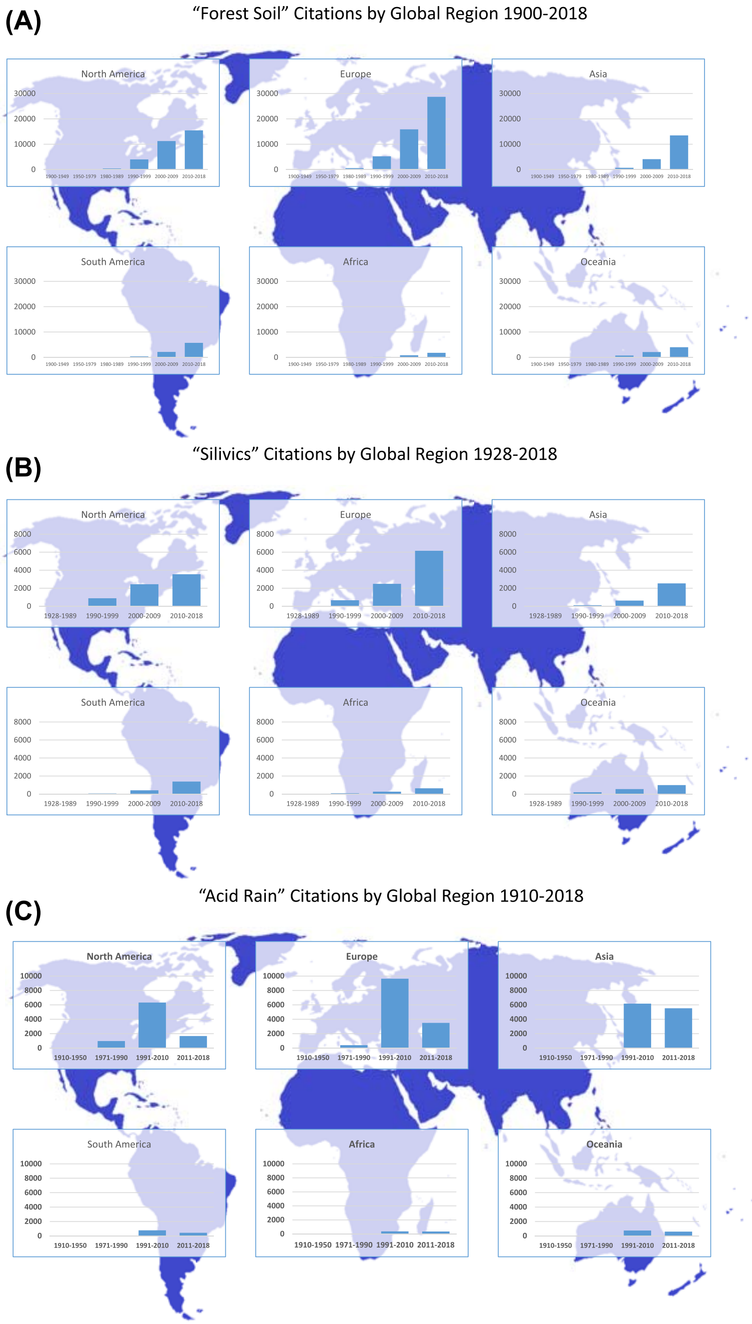


FIG. 19.5

Country of origin for (A) forest soil, (B) silvics, (C) acid rain, (D) biodiversity, and (E) ecosystem literature citations.

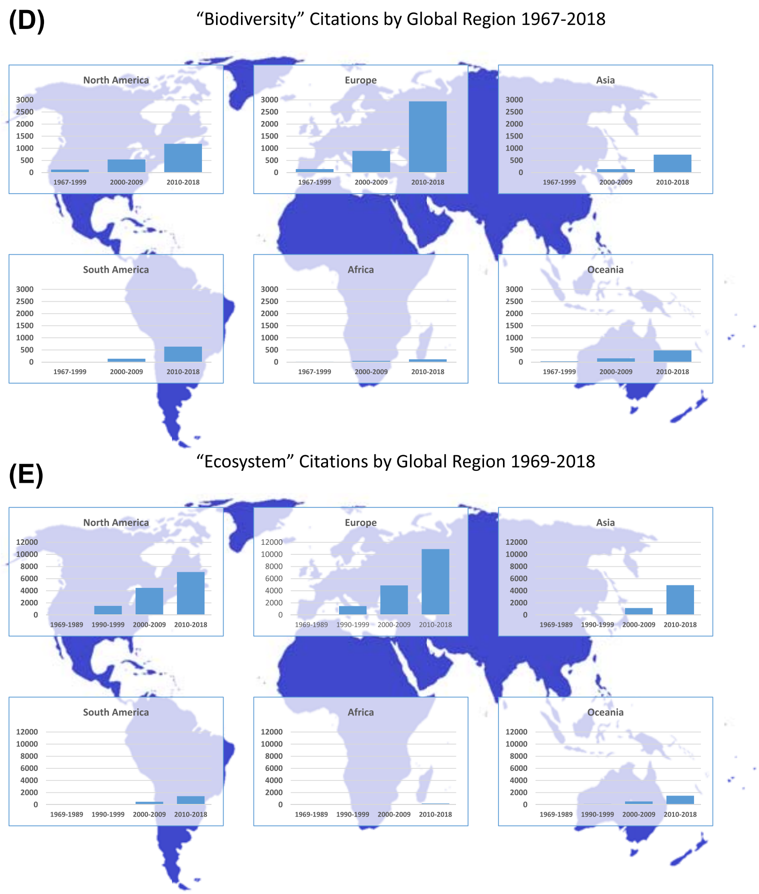


FIG. 19.5 Continued

By 2010–18, publications came from all over the globe, with the top 5 countries being the US, Peoples Republic of China, Brazil, Germany, and Canada.

Forest management and utilization of research networks

One of the first research projects at Bent Creek Experimental Forest (an EFR site established in 1925 in the mountains of western North Carolina) examined the impacts of forest and agricultural cover on surface runoff, erosion, and infiltration rates. Beyond this EFR, one of the first watershed scale treatment demonstrations was conducted at Coweeta Hydrologic Laboratory (established in 1934), also in western North Carolina. The mountain farm experiment, implemented in 1940, mimicked common land use practices of crop production, pasture, and a wood lot in a single 23-acre watershed to determine changes in stream flow and soil erosion. Also, Coweeta supported the 'exploitive logging' experiment (1942) where log skidding practices mimicked those of the 1930s and 1940s. Exploitive logging practices felled and skidded trees downhill in coves and along creeks using horses and tractors. The sediment produced with this logging practice was 50-times greater than clear cut logging with a cable-yarding system and led to the realization that road construction and wood forwarding equipment were the primary sources of sediment production during a logging operation, thereby opening a period of road development research at Coweeta (Swift, 1988; Swank et al., 2014).

One of the first forest soil research studies (late 1950s) initiated on an EFR was by Lou Metz and Carol G. Wells at the John C. Calhoun Experimental Forest (EF) in South Carolina. Their research examined the potential for reforestation to improve degraded agricultural land in South Carolina by quantifying soil fertility and chemical changes following the establishment of loblolly pine (*Pinus taeda*) on an abandoned cotton farm. The Calhoun EF was established in 1947, with research being officially terminated in 1962. Despite this termination of research activities, the site continues to support soil and ecological research through the collaborative efforts of Duke University, the NSF, the Mellon Foundation, and the USDA Forest Service. Recent efforts have designated the Calhoun EF as the 'Calhoun Critical Zone Observatory' and the persistence of the Calhoun EF demonstrates the value of maintaining datasets, records, and sample archives for future generations (Richter et al. 1994; Richter et al., 2014).

Forest management impacts on soils: meta-analyses

Forest management (i.e., harvest, site preparation, changes in plant species composition and fertilization) impacts soils largely through its influences on the input of plant material to both surface soils via leaf fall and wood inputs and to subsurface soils via root mortality and turnover, with inputs greatly increased following harvest or site preparation actions. These management activities can also cause other changes such as altering quality or amount of plant inputs with a shift in species composition, increased nutrient supply following fertilization, or potential alteration of water drainage patterns following earth moving activities (Lal, 2005). There have been several meta-analyses of forest management studies conducted to better understand their collective results. One such analysis used data from 73 observations from 26 locations in 8 countries on 5 continents (Johnson and Curtis, 2001). The analysis focused on forest management effects (harvesting, fire, and fertilization) on soil C and N in the A-horizon; omitting O-horizon impacts due to the high variability in site conditions and site preparation practices. No consistent response of soil C or N was documented due to harvest or fire, with some sites showing increases and some decreases. However, fertilization or the presence of N_2 fixing plants resulted in an overall increase in both total C and N.

This review by Johnson and Curtis (2001) inspired another more extensive meta-analysis of soil C responses to harvesting from 432 sites across the temperate forests of the United States, Europe, Australia and Asia (Nave et al. 2010). The harvest treatments included thinning or clearcutting, stem only or whole tree harvest, along with residue removal levels including none, all, burning and post-harvest tillage. Similar to the findings of Johnson and Curtis (2001), Nave et al. reported high variability in the O-horizon, although, generally, harvesting resulted in an overall decline in O-horizon C. Mineral soil responses were best explained by soil order; Alfisols and Spodosols showed no response, whereas many Ultisols and Inceptisols lost soil C following harvest, but the decreases were transient.

A third meta-analysis further broadened the scope of examining soil C and N responses to land management. This analysis included temperate, boreal, and subtropical forests across North America and Europe; representing 64 forest biomes at 63 locations (Thiffault et al., 2011). Again, soil C responses to harvesting varied among sites, with no clear difference between stem only and whole-tree removals, although O-horizons following whole-tree harvest had more frequent negative responses. In terms of forest biome-level responses, boreal forest soils had a greater negative soil C response compared to temperate forests. Overall, only one site had C losses from the mineral soil following either stem only or whole tree harvest, suggesting that this might have been due to its low initial organic C content. Thiffault et al. (2011) suggest that a final conclusion concerning the impacts of harvesting on soil C and N cannot be reached until data are available from long-term experiments that follow a forest through the entire development of the ecosystem or rotation of the forest in question.

A recent analysis by Egnell (2017) examined data from Nordic countries, 16 publications from 72 experimental sites, to assess the impacts of increasing harvest intensity on site productivity. Data showed that a regenerating stand of Norway spruce (*Picea abies*) was negatively affected by slash removal compared to stem only harvest, while Scots pine (*Pinus sylvestris*) was unaffected. Stump removal in Scots pine harvest actually had a positive growth affect. Inconsistency was partially accounted for by differences in the advanced regeneration onsite following harvest.

Forest management impacts on soils: repeated sampling studies

Research examining the long-term impacts of land management on soils include site based studies that are long-term by design or those that come about due to the efforts of soil scientists to find and re-sample older study sites. Long-term soil studies with direct resamplings, as opposed to paired plots or chronosequences, are relatively rare and those in forests rarer still (Yanai et al. 2000; Richter et al., 2006). One of the longest running forest soil resampling studies is from Broadbalk and Geescroft Wilderness from the renowned Rothamsted Experiments in the UK where sites have been under afforestation and investigation since 1882 (Poulton, 2006). These small fallow plots (0.2 and 1.3 ha, respectively), however, focus on afforestation as opposed to forest management alternatives.

Early repeated sampling research examining long-term effects of forest management focused on forest harvest and whether tree removal, particularly whole-tree removal compared to stem only, would deplete soils of N, the nutrient most often found to be limiting to temperate and boreal forest growth. Calcium (Ca) removal was also of interest as this nutrient was considered particularly susceptible to leaching by the inputs of acidic deposition (see section 4.0 in this chapter) in addition to harvest removals (Johnson et al., 2016). For example, Johnson et al. (2002) conducted a comparison of the 15 year post-harvest soil response to sawlog only or whole-tree harvest by re-sampling sites across the southeastern US, where Ulitsols and Inceptisols dominate. Fifteen years after harvest, soil C differences between sawlog and whole tree harvesting were not significant and at one site both treatments resulted in an increase in soil C compared to pre-harvest levels. The site with increased C was revisited again after 33 years (Johnson et al., 2016) and there was no change in soil C between 15 and 33 years. However, Oa horizon mass and nutrient content was significantly greater in whole tree harvesting as compared to the sawlog only treatment. In another study, changes in soil C for up to 17 years following one of several management practices including, sawlog, whole tree harvesting, plantation establishment, and no disturbance had no consistent response, which showcases the importance of using an appropriate reference to understand long-term impacts (Knoepp and Swank, 1997).

Repeated soil samplings relative to harvest removals have also been prevalent in forests growing in other countries. In their review, Thiffault et al. (2011) identified 21 of 53 studies from these two regions with another 10 studies from the UK and Finland. Work has continued on this topic with re-sampling efforts assessing whether early effects persist beyond 15 yrs. For example, a more recent Swedish study extended sampling over an additional 10 years from age 15 to 25 and compared whole tree to conventional stem only removals (Brandtberg and Olsson, 2012). The work of Brandtberg and Olsson (2012) is notable as they found significant cation losses. At age 15, whole tree harvesting lowered Ca and Magnesium (Mg) contents, but by age 25 no difference in humus or 0−10 cm mineral soil cation contents were detectable. The mechanisms for this pattern could be that slightly greater tree growth after sawlog harvesting increased nutrient uptake and/or greater soil acidity after whole tree harvesting increased mineral weathering. Mineral weathering is difficult to measure and only repeated sampling efforts such as these can potentially provide insights.

Forest management impacts on soils: cross-site comparisons (LTSP)

The North American Long-Term Soil Productivity cooperative research program (LTSP) was established to understand the long-term impacts of clearcut harvesting, compaction, and organic matter removal across a wide range of forest sites. The LTSP is the world's most extensive and long-term coordinated effort to address questions of sustainable productivity in managed forests in response to soil disturbance. The study began in 1989, as a "grass roots" proposal by forest managers and research scientists that grew to a national program of the USDA Forest Service (Powers, 1989; Powers et al., 2005; Powers et al. 2014), with four USDA Forest Service EFRs being pivotal to piloting the experiments. Soon after, the study expanded to other sites and forest types and in 1990 the British Columbia Ministry of Forests adopted the LTSP concept as a high priority program with two installations established by 1994. Independently, the Canadian Forest Service and Ontario Ministry of Natural Resources began experiments in Ontario that closely paralleled the LTSP design, and the two programs merged in 1996 to form an expanded network. Now more than 100 LTSP and affiliated sites comprise this network addressing basic and applied science issues of forest management and sustained productivity. The forest lands covered by the network include major forest types, soils, and climatic conditions. These sites are protected from conflicting uses and remain dedicated to long-term research.

After 10 years, many sites showed that complete removal of surface organic matter led to declines in C concentration in the mineral soil to 20 cm depth and also reduced nutrient availability. However, total soil C storage appears unchanged, in part explained by bulk density changes following disturbance and the inputs of C from root mortality in the harvested sites. Biomass removal from harvesting had no influence on forest growth during the first 10 years and total stand biomass was either unaffected or, in the case of aspen (*Populus spp*.), decreased by soil compaction, due to a reduction in root suckering. The effect of compaction on forest productivity depended on soil texture, the degree of understory competition and a soil's initial bulk density. Productivity declined on compacted clay soils, increased on sands, and was generally unaffected if an understory was absent (Ponder et al., 2012). Sites with initial low bulk densities derived some water storage benefits from compaction; however, recovery varied by climatic regime, being particularly slow in frigid soils. Vegetation control consistently enhanced planted tree biomass regardless of climate and generally increased total stand biomass. For many of the site types and species investigated, harvest-related organic matter removal and soil compaction (excepting aspen vegetative reproduction) did not result in large losses in stand biomass 10 year after harvest.

Further, results out to 20 years suggest that forest site productivity in North America is generally highly resistant to initial disturbances, and for sites showing changes following treatment, remaining sites were characterized by a high degree of resilience to the one-time removal of even all aboveground organic matter. Overall, neither soil properties nor planted tree growth have shown consistent effects from removals. Critically, by examining responses to treatments across a large network of diverse sites, LTSP has improved both continental scale and site specific understanding of the fundamentals of sustaining site productivity, and support the need for regional down to local scale guidelines for forest harvesting and biomass removals (retention) levels. Many LTSP installations are reaching 25 years of age and this self-supported research network has continued to grow and incorporate new affiliate studies and investigators.

Acid rain impacts on forest soils

Anthropogenic emissions of sulfur and nitrogen compounds into the atmosphere increased dramatically with the advent of the industrial revolution around 1760. The atmospheric mixing of these pollutants with water results in atmospheric acidic deposition or more commonly referred to as acid rain, which was perhaps the first global environmental problem that resulted in worldwide research into causes, impacts, and methods of recovery. The earliest work in our literature search was published in 1910, and between 1910 and 1949, 87 papers were identified. From 1979–89, almost 1500 papers were published and from 2010–18 the number was greater than 19,000 (Table 19.1). There was an interesting shift in the origin of publications during this time period (Fig. 19.5C). From 1910–1949, 6 countries were identified, with the US, United Kingdom and Canada as the top three. During 1980–1989 publication origin was concentrated in the US, Canada, England, Federal Republic of Germany, Germany and Japan with the most recent acid rain literature (2010–18) originating in People's Republic of China, US, India, Germany, and Japan along with countries in all other continents, excluding Antarctica.

The inclusion of acid rain as a topic within forest soils research begins in 1980. This focus remains a small part of the acid rain literature, with about 900 publications during the 2010–18 time period. Research into the impacts of atmospheric acid deposition to forested ecosystems began in the mid-twentieth century across Europe and then moved to the northeastern US (Likens et al., 1972; Likens and Bormann 1974). Acid deposition is defined as the deposition of H ions as well as those ions or aerosols (SO_4, NO_3, SO_2, or NOx) having the potential to produce acid in the soil (Abrahamsen, 1984). The creation of the US Environmental Protection Agency and passage of the Clean Air Act (both in 1970) and the Clean Air Act Amendment (1990) (CAA), along with the passage of additional emission regulations resulted in significant declines in sulfur dioxide and nitrous oxide emissions, with these reductions achieving the goal of reducing sulphuric and nitric acid concentrations in rainfall. USEPA reported that by 2011 sulfur deposition across the United States had decreased by over 50% (USEPA 2015) resulting in the shift in research from impacts to processes of recovery. The National Atmospheric Deposition Program/National Trends Network (NADP/NTN) collects wet atmospheric deposition at 250 monitoring sites across the US, and these have become critical to understanding the long-term depositional trends for the entire country.

Research efforts on acid deposition and soil acidification

As described by Gorham (1998), acid deposition was identified in 1757 (Home, 1757) and described around Manchester, England in 1852 (Smith, 1852, 1872), but links with soils and forest soils, in particular, did not begin in earnest until the early 1900's (Rusnov 1919; Katz, 1939). Sulfur dioxide from fossil fuel combustion was linked to acid deposition (Barrett and Brodin, 1955) with impacts extending from industrial or energy production facilities to rural environments (Galloway et al., 1982), particularly in lakes and forests (Schindler, 1980; Ulrich et al., 1980). It was also recognized as a source of concern about forest decline ("Waldsterben"), largely in Europe, which was a catalyst for an expanded effort in acid rain effects on soil properties and processes.

After decades of measuring inputs of acid deposition and changes in lake pH, quantifying the rate and extent of soil acidification attributable to acid deposition became a critical question (Oden, 1976; Likens et al., 1979). Forest soils are by nature an acidic medium (Tabatabai and Olson, 1985) and anthropogenic acid rain is only one source of acidity input to forest ecosystems (Binkley and Richter, 1987; Ruess and Johnson, 1985; Sollins et al., 1980; Ulrich, 1980), which greatly complicates efforts to isolate the impact of anthropogenic versus natural sources of acidity on processes of acidification in soil (Driscoll and Likens, 1982; van Breemen et al. 1983; Krug and Frink, 1983; Richter, 1986).

The ability for soils to buffer acidity was a topic of debate with some investigators arguing that soil buffering capacity exceeded acid inputs (Wiklander, 1973; Krug and Frink, 1983; Tabatabai and Olson, 1985), others however demonstrated that soil solutions could be acidified even in the presence of soil buffering (Ruess and Johnson, 1985). Van Breeman et al. (1983) highlighted the distinction between soil pH, which may change quickly, versus base saturation, a soil chemical property that changes more slowly and should be evaluated over the longer-term.

Over the second half of the 20th century substantial acidification research efforts were initiated in Europe (Abrahamsen et al, 1994; Schulze et al., 1989; Lapenis et al., 2004), North America (Likens et al., 1979; Johnson and Lindberg, 1992; Markewitz et al. 1998), and Asia (Bashkin, 1998; Hao et al., 1998; Duan et al. 2016; Nakahara et al. 2010) to consider the acid neutralizing capacity (ANC) of forest soil. In this context, ANC is defined as the buffering capacity of forest soil to neutralize acidic deposition.The buffering of acidity requires the weathering of silicates or the acidification of the soils, largely through a reduction of base saturation. Rock weathering is a slow process and a challenge to quantify even at the decadal scale and the presumption is that acid inputs beyond weathering lead to a decline in soil base saturation and therefore acidification (Johnson et al. 1968; Johnson 1984; Likens 2013).

Acid addition experiments have provided a controlled means to measure soil change. In the 1970s, research in Norway created acidified irrigation experiments (pH range 5.6 to 2) and generally found that pH levels of 3, 2.5, and 2 in the acid deposition treatments all significantly decreased soil pH and base saturation compared to the water only controls. These changes were more evident in the O and E horizons than in the Bs horizon (Stuanes and Abrahamsen, 1994). In addition to plot-based studies, two large scale studies, Fernow Experimental Forest Watershed Acidification Study (Adams et al. 1993; Adams et al., 2006) and Bear Brook Watersheds in Maine, US (Fernandez et al., 2003), applied varying rates of ammonium sulfate on forest soils to investigate acidification in streams and soils. Additions to the treated Fernow watershed equaled two times ambient inputs in three applications per year mimicking seasonal deposition patterns; total = 32.5 kg S ha^{-1} and 28.4 kg N ha^{-1}. At Bear Brook ammonium sulfate was applied bimonthly at a similar rate (total = 28.8 kg S ha^{-1} and 25.2 kg N ha^{-1}). In both experiments, watersheds demonstrated a clear elevation in stream Ca and Mg compared to the reference watershed. The soils within these watersheds also showed associated changes in exchangeable bases.

As knowledge of acid deposition and its effects grew, it became apparent that the effects went beyond acidity, and that other nutrients were involved as well. The need to quantify solution fluxes of all macro-nutrients in the ecosystem also led to a more holistic view of the biogeochemical balance of forest ecosystems. Nitrogen, in particular, grew as a focus of concern as nitrogen oxide emissions resulted in nitric acid inputs to forests that over time were thought to possibly exceed system uptake and storage capacity leading to nitrogen saturation of the ecosystem (Aber et al., 1989, 1998, 2003). This growing focus on the biogeochemical balance of the ecosystem was based on the conservation of mass and the principle of electrical neutrality (Cronan, 1980; Ulrich, 1987).

Recovery from acidic deposition

The decline in acidic deposition began in the 1970s and research examining forest recovery across Europe and North America began soon after. Much of this research used soil solution as a proxy for extractable soil chemistry to examine the responses of forest health, streams and soils. The ILTER network studied 25 watershed scale focused sites across Europe. The UNECE International Cooperative Program has been examining 25 years of recovery to declining deposition using either stream export or soil solution data (Vuorenmaa et al., 2018). Studies of recovery in European beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* Karst. [L.]) ecosystems have been underway for more than 40 years near Solling, Germany. As deposition declined these and other research sites, demonstrated a decrease in stream and soil solution concentrations and fluxes of acid constituents. Indicators of recovery were characterized as resilient or adaptive (Burkhard et al., 2009), representing ecological integrity (nutrient retention), production of timber and fuel, and regulating services (air and water quality and soil nutrients) (Griffiths et al. 2016; Meesenburg et al. 2016). Ecological integrity was resilient to acid deposition while exchangeable base cations adapted to acid deposition, suggesting a new equilibrium had been reached. Woody biomass production also adapted to soil acidification and ecosystem N loading and even saturation. Air and water quality were also resilient to deposition, recovering quickly, while soil solution base cation to aluminum ratios had adapted to changes in deposition.

Long-term measurements have allowed for assessments of air pollution control measures and the continued monitoring of acidification or alkalinization of forest soils. For example, in the northeast US, Lawrence et al. (2012) resampled six red spruce (*Picea rubens)* sites in 2003/4 that had been sampled in 1992/3, finding some increase in pH (~0.2 pH units) at half the sites and a clear 20–40% decline in exchangeable Al in all sites. Working in Ontario, Canada, Miller and Watmough (2009) used archived soil from 1986 and resampled 17 sugar maple (*Acer saccharum*) stands in 2005. After 20 years of declining SO_4 deposition, they found that pH and exchangeable bases had still decreased. In contrast, a retrospective study in Vienna, Austria covering the period 1984 to 2012 found a pH increase of 0.6 pH units and observed a general recovery of topsoil acid status (Berger et al., 2016).

Changes in global atmospheric chemistry

Acid rain initiated global interest in atmospheric chemistry and as regulatory action has improved air quality in some countries, the interest has since moved to examining recovery patterns from past pollutant inputs. This monitoring has verified the continued rise in CO_2 concentrations and has been identified as a key concern for global climate change and carbon cycling. The interest in soil organic C was evident prior to research on climate change with the first publication identified in 1928. However, between 1928 and 1979 only 31 publications were found in our search. During the next few decades there were remarkable increases, with the most recent counts (2010−18) in the neighborhood of more than 20,000 publications. Prior to 1969, only the US had soil carbon publications. In the following decade (1970−79), publications were originating from US, Canada, and USSR, as well as from the Federal Republic of Germany, Germany, and Sweden. Most recently, publications have originated from the US, People's Republic of China, Germany, Canada and Brazil and other countries representing 6 of the 7 continents. See Chapter 11 for complete coverage of soil C research.

Forest soil biodiversity

There is wide interest in understanding the importance of the biological component of soils to their processes and function within the forest ecosystem. This resulted in an increase in publications examining the diversity of microbial life, and micro- and macro-arthropods within the soil system (Coleman et al. 2018). 'Biodiversity' in forest soils was a term first published in 1967 but through to 1989 only 4 publications were identified. Publication numbers rapidly increased to 9400 over the 2010−18 period. Country of origin for biodiversity publications varied with 57 countries listed from 1967 to 1999; the top five were the US, Canada, England, France, and Australia (Fig. 19.5D). The following decade (2000−09) listed 98 countries. Countries of origin in 2010−18, were located across the globe with the US, Germany, People's Republic of China, Brazil, and Australia producing the largest number of publications. With the use of new analytical tools, microbial diversity publications are becoming more common, but will not be discussed here (see Chapter 15). However, there are a great number of publications from studies focused on long-term changes to faunal biodiversity in forest soils, and discussion of that work follows here.

Long-term forest soil fauna biodiversity studies

Some of the earliest scholarly work on soil invertebrates dates back to Charles Darwin (1881), who wrote on the importance of earthworms in soil formation and soil profile development. Darwin's observations on the activities, and effects, of earthworms took place over a 40-year period during the time he and his family lived in southern England and may represent the earliest documented long-term study involving soil invertebrates. Darwin established that surface casting (deposition of ingested soil on the soil surface) by earthworms, although representing relatively small amounts of soil at any one point in time, can accumulate to result in the partial (the sarsens at Stonehenge were embedded to a depth of 30−40 cm) or total burial (stones up to 12 cm diameter, weighing > 1 kg) of sizable objects at the soil surface, potentially changing soil profiles over time (Butt et al., 2016).

Another well-documented influence on soil invertebrate communities is that of land-cover or land-use changes. This work has focused on soil biota (microbes and fauna) responses to agricultural practices, with many studies documenting the relative benefits of conservation tillage practices on the total biomass, diversity and functionality of soil invertebrate assemblages (see, Briones and Schmidt, 2017). Relative to agroecosystems, there has been much less work addressing these issues in forest or rangeland ecosystems, and most of these are "natural ecosystem" efforts and were conducted in EFRs and LTER sites. For example, at the Calhoun EF where plantation-based forestry has followed cotton agriculture (Richter et al., 2014), current work examines how this land use change has altered invertebrate assemblages over 40 years of forest recovery. Results indicate that undisturbed vegetation and soils have the greatest species richness, but planted pine forests had the greatest similarity in soil invertebrate assemblage to the relict hardwood stands. Pastures and cultivated fields were more similar to each other, and both had a higher proportion of occurrence for non-native earthworms (Callaham et al., 2006). Furthermore, recent reports from a long-term study in Poland, where soil faunal diversity was evaluated under monoculture stands of 14 different tree species (34 year old), showed that individual tree species can influence the richness of particular components of soil invertebrate diversity (e.g., nematode diversity was highest under birch [*Betula pendula*], and lowest under Douglas-fir [*Psuedotsuga menziesii*]), and birch was also highest in an integrated index of total soil invertebrate diversity (Mueller et al., 2016). These authors further found that the total diversity of the 14 monoculture stands was not well represented by any one of the stands, presenting the argument for supporting landscape-level forest mosaics if the goal is to maintain optimal diversity of soil invertebrates.

Forest soil biodiversity: disturbance

Disturbance from hurricanes and invasive species, as well as effects of secondary forest succession have been ongoing at the Luquillo EF in Puerto Rico. For an excellent, comprehensive review of soil biological (including microbes) research at Luquillo, see González and Lodge (2017). Highlights from soil faunal research in Puerto Rico include important findings on decomposition of leaf litter and coarse wood, with insights into the importance of millipedes and termites for the decay of these substrates, respectively. In the case of termites and wood decomposition, González et al. (2008) found that termites contributed more to the decay of wood than could be otherwise accounted for by simple climatic variables, serving to emphasize the critical nature of soil fauna in this ecosystem.

Land-use and land management impacts on soil invertebrates have been the objective of long-term experimental manipulations at the Konza Prairie Biological Station and LTER site in the tallgrass prairie biome of east-central Kansas. One of their experiments manipulated fire, aboveground biomass (mowing hay), and nutrient additions over a 30- year period results show that fire exclusion, absence of mowing, and nutrient addition resulted in a complete ecosystem transition from grassland to incipient forest vegetation. This state-change also influenced soil fauna community composition, as documented by Callaham et al. (2003), near the midpoint of the experiment. The authors found that after 13 years of experimental manipulation, the invertebrate community had shifted with the primary effects being an increase in the abundance and biomass of non-native earthworm species when fire and mowing were excluded, and shifts in the biomass of herbivorous insect larvae, usually more abundant with nutrient addition and less abundant with mowing. These findings inform previous observations about earthworms (James 1982), which indicated that native earthworm species were more abundant in frequently burned prairie soil than in unburned watersheds. Further, Darby et al. (2013) found that plant-feeding, fungal-feeding and omnivore/predator feeding guilds of nematodes were generally more abundant in burned plots, whereas bacterial-feeding nematodes were favored by fire exclusion. All these responses were likely indirect responses to the changes in vegetation induced by the treatments, and the attendant changes in organic matter inputs and leaf- and root-litter quality.

In boreal forest ecosystems in Finland, a long-term study revealed that the diversity of surface-dwelling beetles, among other biotic components of the ecosystem, could be restored with the use of prescribed fire and the creation of dead wood (Vanha-Majamaa et al., 2007). These authors concluded that modest modifications to harvest practices in Norway spruce (*P. abies*) forests, which include leaving small quantities of wood on site, and retaining small pockets of aspen (*Populus tremula*), provides a habitat mosaic that promoted greater biodiversity.

Forest soil biodiversity: introduced earthworms

Gates (1967) described earthworm specimens from locations all across the Great Basin, and was the first to report earthworms in Nevada, Utah, and Arizona. Importantly, the specimens collected, identified, and reported for Arizona came from the Sierra Ancho EF. These collections included at least three non-native species, and one native species, and offers an opportunity for present-day researchers to go back to these sites to evaluate how these populations may have persisted or changed over the intervening 50 years.

Forest soils research: long-term studies using the ecosystem approach

The word ‘ecosystem’ was coined by Sir Arthur George Tansley in 1935 as ‘a group of interconnected elements, formed by the interaction of a community of organisms with their environment.’ The ecosystem approach to ecology and forest science was presented in Eugene Odum’s ‘Fundamentals of Ecology’ in 1953, which evolved into ‘Systems Ecology: An Introduction’ in 1983. This approach to research marked a shift from conducting narrow disciplinary research studies to experiments designed to describe an entire ecosystem response in terms of biological, physical, chemical and environmental processes. Publication of forest soil and ecosystem research increased rapidly, with more than 3100 occurrences in 1989–2000 and 16,500 in 2010–18. This research method is also evident with the inclusion of the term ‘water quality’ in literature beginning in 1977; water is viewed as the integrator of many ecosystems. Early publications (1969–79) that included the topics of forest soils and ecosystems originated in the Federal Republic of Germany, Poland, and Canada (Fig. 19.5E). Between 1980–89, the US, Federal Republic of Germany, Canada and France led the number of publications. The US and Germany remained the two countries with the greatest number of publications on ecosystems until the 2010–18 period when People’s Republic of China was also included in the top three countries (US, People’s Republic of China, and Germany).

The ecosystem approach to forest research brought along with it an interest in long-term responses as evident by the inclusion of the keyword ‘long-term’ in publications beginning in 1975. Publication numbers have increased each decade reaching over 5000 in 2010–18, indicating the importance of and interest in long-term studies in forest soils research. The value of long-term research to ecosystem science was explored through the use of a survey completed by scientists in the field (Kuebbing et al., 2018). The survey found overwhelming support for the continuation of long-term research sites due to their marked contribution to ecosystem understanding with the note that both observational and experimental approaches were necessary. Measurement of long-term responses may yield data that identify factors that regulate ecosystem responses to disturbance or change over time and answer questions not imagined at the initiation of the experiment. Lindenmayer et al. (2010) discuss the detection of these 'ecological surprises' by utilizing long-term and historic data along with taking advantage of natural disturbances. This type of research is essential as ecosystem responses to climate change and multiple stressors becomes evident.

Rothamsted experiment station: wilderness experiment

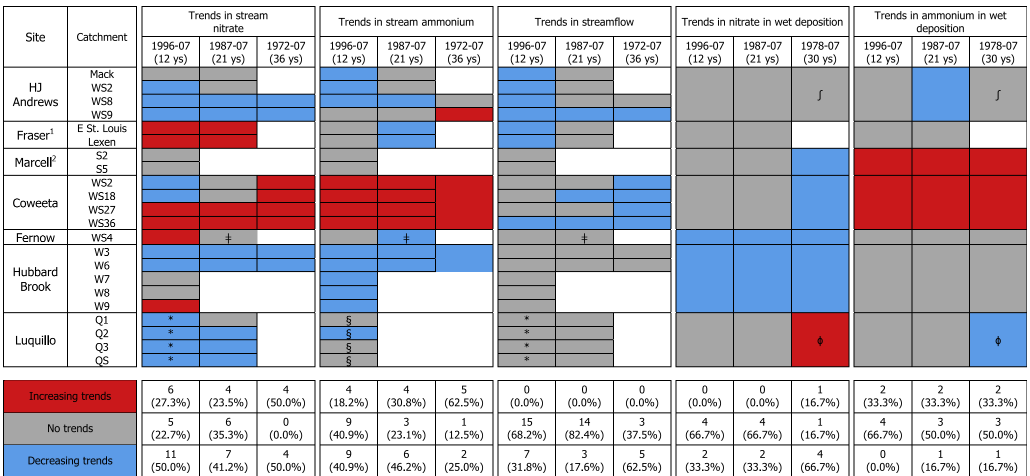
The potential for soils to sequester carbon has become a central focus of soil science and was examined using data from long-term soil studies (>20 years) across Europe (Smith et al., 1997). As previously noted, afforestation studies on Rothamsted Experimental Station dating back to the 1800s have long-term soil carbon measurements. Collectively, these data suggest that afforestation of abandoned arable land could result in significant and large scale carbon sequestration world-wide. In addition, soils from these sites have been studied for many other attributes including: soil pH impacts on organic matter (Tonon et al., 2010); acidic deposition effects on soil chemistry (Blake et al., 1999); methane oxidation potential (Maxfield et al., 2011); and soil biodiversity of earthworms and nematodes (see Section 6.0). Rothamsted has an archive containing over 300,000 plant and soil samples, dating back to 1843. Archived soils have been used to examine long-term changes in soil chemistry due to land management and climate. Additionally these samples have contributed to a greatly improved understanding of soil processes associated with changes in the vegetation community through the analysis of phytolith content and source (Guntzer et al., 2012) as well as carbon isotopes (Jenkinson et al., 2008). These provide an excellent example of how valuable archiving and subsequent analyses of archived samples can be in understanding soil responses to management and a changing environment (MacDonald, 2018).

Long-term forest ecosystem responses and "ecological surprises"

Due to the long-lived nature of forests, full understanding of forest management and disturbance responses require long-term research as their impacts can also be long-lived (Keiser et al., 2016). The ecosystem approach to forest management research differs from simply evaluating harvest systems and site preparation on vegetation by incorporating measurement of changing vegetation, successional trajectories, stream flow and chemistry, biogeochemical cycling as well as forest soil chemistry and biological processes. Small watershed studies use the ecosystem approach, measuring inputs as wet and dry deposition and outputs via streamflow for a net budget and within-watershed processes to assess patterns of biogeochemical cycling (Campbell et al., 2013). Because watersheds have a defined boundary, flux (inputs, outputs, transformations) measurements are scaled, making them useful to examine climate and land use change impacts on the hydrologic cycle and to simulate and model biogeochemical cycling. The persistence in taking periodic measurements over the long-term length of these studies informs not only management, but provides understanding of basic ecosystem processes such as regulating soil chemistry, aboveground biomass, and nutrient fluxes. Budgets of pools and fluxes have been published for Ca and other cations (Likens et al., 1998; Swank et al. 1988a; Knoepp and Swank, 1994; Campbell et al. 2016), C (Fahey et al., 2005; Pregitzer et al., 2004; Lovett et al. 2013), and N (Likens et al., 1970; Swank and Vose, 1997; Brookshire et al. 2007, 2011; Lovett et al. 2018; Argerich et al., 2013). These studies provide detailed examination of acid deposition impacts on nutrient movement and subsequent ecosystem recovery (Likens and Buso, 2012; Likens and Lambert, 1998; Rosi-Marshall et al., 2016), effects of climate change (Lutz et al., 2012), and both the initial and long-term impacts of forest management (Swank 1988b; Knoepp et al., 2014; Valipour et al. 2018; Dahlgren and Driscoll, 1994; Keiser et al., 2016).

Long-term ecosystem research projects often evolve from studies that examined experimental manipulations (see section 3.0, this chapter). Examples are USDA Forest Service EFRs, established to examine the impacts of land use and forest management, and often using the paired watershed approach. The long-term studies at these sites examine multi-decade trends in stream chemistry in reference watersheds across the US. A prime example was the examination of trends in stream nitrate concentration that highlighted the importance of long-term measurements and the effect of just how "long", long-term needs to be (Argerich et al., 2013) (Fig. 19.6). Here, data from 22 forested reference watersheds across 7 EFs showed that patterns of changing stream nitrate concentrations varied by location as well as length of time and the period of measurement. This demonstrates the importance of continuing to monitor forest ecosystems to more fully understand how they change over time.

Some of these long-term research sites have resulted in "ecological surprises", highlighted by Lindenmayer et al. (2010). A classic example is found at Hubbard Brook Experimental Forest, where the measurement of acid deposition impacts on nutrient fluxes showed impact on leaching losses of soil Ca. A later vegetation removal experiment showed not only an increase in stream NO_3 (Likens et al., 1970; Dahlgren and Driscoll, 1994), but also increased Ca losses that were attributed to high



[1]May to October, [2]April, May, June, July, October, *Period of 1997-2007, ‡Period of 1989-2007, ʃPeriod of 1980-2007, §Period of 1998-2007, ϕPeriod of 1985-2007.

From: Argerich, A., S.L. Johnson, S.D. Sebestyen, C.C. Rhoades, E. Greathouse, J.D. Knoepp, M.B. Adams, G.E. Likens, J.L. Campbell, W.H. McDowell, and G.G. Ice. 2013. Trends in stream nitrogen concentrations for forested reference catchments across the USA. Environmental Research Letters 8 (2013) 014039 (8pp).

FIG. 19.6

Trends in long-term stream chemistry for USDA Experimental Forests. Number (above) and percent of streams sampled showing increasing, no, or decreasing trends in nitrate and ammonium nitrogen concentration.

rates of nitrification and NO_3 formation. Use of these data, along with data from a whole tree harvest experiment that included estimates of Ca removal in wood, suggested that soil weathering would not be sufficient to replace the losses (Federer et al., 1989). Soil acidity and Ca deficiency was also identified as a potential cause of sugar maple (*A. saccharum*) decline across the northeastern US (Ouimet et al., 1994). The synthesis of these findings led to the whole watershed treatment with wollanstonite ($CaSiO_3$) to add Ca without affecting pH. This effort to mitigate the Ca loss from decades of acidification, in turn, resulted in increased export of N from the watershed (Rosi-Marshall et al., 2016) highlighting the importance of nutrient balance and the possibility (likelihood) of unintended consequences occurring when only one aspect of a disturbance is considered during mitigation.

Another "ecological surprise" was identified during the long term study of responses to a 1976 clear-cut at Coweeta Hydrologic Laboratory, an EFR in western North Carolina. Following the clear-cut, the expected increases in nutrient fluxes occurred, returning to near baseline 6 years after cutting. However, another 7 years later (13 years after cutting), N (as NO_3) export began to increase again, with the trend continuing to date (Jackson et al., 2018). In an examination of the response, Webster et al. (2016) identified this as a regime shift in the regulation of stream N export. Reference watersheds generally display a biological regulation (Webster et al., 2016; Jackson et al., 2018; Adams et al., 2014; Adams and Kochenderfer 2014), and seasonal patterns that coincide with increased soil biological activity in early summer and have a negative relationship between stream flow and N concentration. However, the clear-cut watershed shifted to hydrologic regulation, in which stream N concentrations increased with increasing stream flow. This "ecological surprise" suggests that while forested watersheds often display considerable resilience to disturbance there is a tipping point where processes do not return to 'pre-treatment' conditions — at least on the scale of decades.

A third example of an "ecological surprise" is the response to, or actually lack of response, to tree mortality resulting from infestation by the mountain pine beetle (*Dendroctonus ponderosae*) taking place in the Fraser Experimental Forest in Colorado. The pine beetle infestation extends across western North America, from Mexico to Canada, causing extensive lodgepole pine (*Pinus contorta*) mortality (Rhoades et al., 2013). Past research in the western pine region, where N deposition is relatively low, has found high stream N concentrations following beetle mortality, but generally lower than following other types of disturbance such as wildfire or logging (Rhoades et al., 2011). In a study examining the long-term records of stream N at the Fraser EF researchers were able to isolate ecosystem effects specifically due to beetle infestation. Using US Forest Service, Forest Inventory and Analysis plots, 165 of which are located throughout the Fraser, it was found that mortality was greatest on plots with large diameter trees located on south-facing slopes, at lower elevations (Vorster et al., 2017). Long-term measurements of stream chemistry at the Fraser, beginning 20 years before infestation, provided baseline data allowing examination of the impacts of this widespread infestation. Watersheds dominated by old growth trees, which were most susceptible, experienced 85% stand mortality resulting in 44% loss of basal area. However, watersheds that had been previously managed (thinned or logged) and had a mixture of second growth and old-growth lost only about 25% of the total basal area. Stream N responded only in watersheds dominated by old growth forest. Watersheds with a mix of forest ages showed no stream response; N released due to disturbance was taken up by the residual vegetation and sequestered in wood and foliage (Rhoades et al., 2017).

Long term research studies yield information about the temporal changes in forest ecosystems and the interactions of soils, vegetation, water and the environment around them. These long-term measurements have also resulted in "ecological surprises" and provided answers to questions that were not considered at the initiation of the experiment. As more experiments become long-term, we would anticipate additional surprises will result in deeper understanding and discovery and interaction of the processes involved in the regulation forested ecosystems.

Lessons learned from long-term forest soils research

General

- Long-term research plays an important role in advancing the understanding of ecosystem function.
- Multi-site research that includes both observational and experimental approaches are particularly valuable.
- Successful networks such as the EFR, LTER, and LTSP require significant cooperation among all researchers and stakeholders, an unusually high degree of commitment, drive among principle investigators, and timely financial support.
- Archived samples and maintenance of long-term meta-data are essential to building on our knowledge and understanding of the role of soils in the world.

Forest management

- Forest management impacts on soil physical and chemical properties have been surprisingly variable, depending on treatment intensity and soil type.
- Expected losses of mineral soil carbon with harvesting have not been regularly demonstrated.
- Soil compaction, presumed to negatively impact future growth, can increase growth on sandy soil types due to improved water holding capacity.
- Repeated sampling studies demonstrate the decadal scale of some soil processes and recovery from short-term harvest impacts.
- Resampling indicated increased surface (0−7.5 cm) soil C only 40 years after harvest.
- Whole tree harvest impacts on surface soil cation contents were no longer detectable in decades-long resampling, although tree declines were evident.

Acid Rain

- Declines in soil pH did not always align with increases in exchangeable acidity.
- Repeated measures were able to identify changes that were not detectable over the short term, and enabled researchers to challenge hypotheses posed about soil change, and guide policy changes and the evaluation of their effectiveness.
- Early debates about potential declines in exchangeable Ca were settled by measured declines in many locations two to three decades after reductions in acid rain.
- Long-term declines in soil pH and acidity in Ultisols of the Southeast US demonstrate that acid forest soils can become more acidic.
- Early predictions of SO_4-soil equilibrium exchange have been support by long-term measurements.

Soil Biodiversity

- Soil invertebrates have small individual range sizes and slow movement making long-term observations required to adequately address their responses to manipulations or perturbations that affect large areas.
- Soil faunal diversity richness differs with tree species composition and shows a long term response to disturbance and species changes showing the importance of maintaining a forest mosaic for the optimal soil invertebrate diversity.
- Sites with native vegetation and ‘natural’ disturbance regime, such as prairie fire, shows the greatest diversity and the least non-native species.

Long term research studies have informed forest management and policy decisions designed to ensure sustained forest productivity in addition to providing other important forest ecosystem services, such as, biodiversity and clean consistent sources of water. Continued measurement of long-term research studies is essential to understanding the interaction of potential stressors on long-lived forest ecosystems including, management, changing species composition and changing climate.

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