Long-Term Soil Experiments: Keys to Managing Earth's Rapidly Changing Ecosystems

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To meet economic and environmental demands for about 10 billion people by the mid-21st century, humanity will be challenged to double food production from the Earth's soil and diminish adverse effects of soil management on the wider environment. To meet these challenges, an array of scientific approaches is being used to increase understanding of long-term soil trends and soil–environment interactions. One of these approaches, that of long-term soil experiments (LTSEs), provides direct observations of soil change and functioning across time scales of decades, data critical for biological, biogeochemical, and environmental assessments of sustainability; for predictions of soil productivity and soil–environment interactions; and for developing models at a wide range of scales. Although LTSEs take years to mature, are vulnerable to loss, and have yet to be comprehensively inventoried or networked, LTSEs address a number of contemporary issues and yield data of special significance to soil management. The objective of this study was to evaluate how LTSEs address three questions that fundamentally challenge modern society: how soils can sustain a doubling of food production in the coming decades, how soils interact with the global C cycle, and how soil management can establish greater control over nutrient cycling. Results demonstrate how LTSEs produce significant data and perspectives for all three questions. Results also suggest the need for a review of the state of our long-term soil-research base and the establishment of an efficiently run network of LTSEs aimed at soil-management sustainability and improving management control over C and nutrient cycling.

Abbreviations: FACE, free-air carbon dioxide experiment; IRRI, International Rice Research Institute; LTCCE, Long-term continuous cropping experiment; LTSE, long-term soil experiment; RSS, repeated soil survey; SFTS, space-for-time substitution; STSE, short-term soil experiment.

With human population doubling to about 10 billion people in 50 yr (Bongaarts, 1995), a number of society's most important scientific questions concern the future of the Earth's soil (Arnold et al., 1990; National Research Council, 2001, Wilding and Lin, 2006)—questions about how food production can be doubled in the next several decades and about how humanity is transforming soils and soils' interactions with the wider environment. We review how long-term soil experiments help address these questions, specifically in quantifying decade-scale transformations in soil physics, chemistry, and biology (Jenkinson, 1991; Leigh and Johnston, 1994; Rasmussen et al., 1998; Richter and Markewitz, 2001; Debreczeni and Körschens, 2003; Tirol-Padre and Ladha 2006).

Long-term soil experiments are field experiments with permanent plots that are periodically sampled to quantify soil change across time scales of decades (Table 1). They are especially valuable if their time-series data are accompanied by a sample archive that can be analyzed long after sample collection. Management treatments are experimentally controlled and, ideally, sampling, archiving, and analyses are well documented and statistically rigorous.

Long-running observations of environmental change are extremely useful to environmental science, management, and education. Long-term records are fundamental to predicting the weather, air and water pollution, river flows, tectonic activity, wildlife populations, and changes in vegetation (Baumgardner et al., 2002; Magnuson, 1990; Palmer, 1968; Park et al., 2005; Robbins et al., 1989; Likens, 1989; Leopold et al., 2005; Christensen, 1989; Walling and Fang, 2003). Although not many soils are studied for more than several years, our scientific understanding of the soil is greatly influenced by a few, highly productive, long-running field experiments (Richter and Markewitz, 2001).

Soils are nonlinear systems resulting from high-order interactions of physics, chemistry, and biology (Young and Crawford, 2004). As such, the details of soil change are not readily predictable as they play out over decades, and temporal dynamics are studied with several approaches, including short-term studies in the lab or field, space-for-time substitutions (i.e., chronosequences), repeated soil surveys, computer modeling, and LTSEs. Some uses and challenges of these approaches are summarized in Table 2.

Short-term soil experiments (STSEs) in the lab and field have produced much of the data that have built the sciences of soil physics, chemistry, and biology. Ironically, STSEs often explore soil processes subject to change over decades, topics such as aggregation, adsorption, complexation, C dynamics, weathering, microbial activity, redox, and soil fertility itself. Scaling up and extrapolation are often a major challenge for STSEs. Small changes or small errors extrapolated across many years can readily bias long-term projections.

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Although STSEs greatly enrich soil concepts and models, most tend to be reductionist, isolating individual components and reactions, and do not examine the whole soil, complete with its high-order interactions and lag times that become apparent only with time. Later in this review, results from four LTSEs illustrate how short-term results can contrast greatly with longer term trajectories. Even so, if STSEs are performed in conjunction with LTSEs, they can provide critical short-term process data in the context of longer term soil change.

Space-for-time substitutions (SFTSs), also called *chronosequence studies*, are used to efficiently examine temporal change in soil, ecosystems, and landscapes (Pickett, 1989; Hotchkiss et al., 2000). For questions of how soils change with time, SFTSs sidestep the great burden of LTSEs, the need for time to pass. The SFTSs are particularly suited for studies of change over geologic time and as such they are widely used to describe soil change over multimillennia (Jenny, 1980). A well-known example describes soil formation along the exquisitely beautiful coastline of Mendocino County, California, where land surfaces have been uplifted tectonically on five occasions during the Pleistocene (Jenny, 1980). The series of landforms displays a grand trajectory of soil and ecosystem development over a million years.

Space-for-time substitutions are, however, indirect in inquiry, purposefully confounding space and time, but thereby leaving open the possibility for faulty interpretation. As a hypothetical example, a SFTS might overestimate rates of soil formation on acidic mine spoils if recent soils are inadvertently composed of materials with greater acidity than those used for older soils (Pickett, 1989). Many scientists are cautious or critical about the use of SFTSs (Gleason, 1927; Hotchkiss et al., 2000; Buol et al., 2003). On the other hand, only SFTSs can describe many soil changes that operate over many centuries and millennia.

Repeated soil surveys (RSSs) are modern soil surveys explicitly designed to describe soil variation across both space and time. While traditional soil surveys produce spatial soil data, a few surveys are now implemented to describe regional soil change through time. Compared with LTSEs, repeated surveys illustrate changes in soil properties not under experimental conditions but across operational landscapes, and thus have the potential to quantify soil change regionally as affected by shifts in regional land uses or other environmental conditions. In contrast to LTSEs, management practices are not controlled, so RSSs are challenged to interpret causes of observed dynamics. Below we discuss results from two notable RSSs that aim to quantify decadal soil change across England and Wales (Bellamy et al., 2005) and across Belgium as well (van Wesemael et al., 2004).

Computer models offer an approach to understanding soil change from the instantaneous to the multimillennial. The role and rationale of models are as much heuristic as they are predictive, as they represent refined hypotheses and depend on linkages with empirical studies. Models are instrumental for making progress in understanding soil change, whatever the time scale, and are most convincing when simulation results are compared with observational data. Whether observations are from STSEs, SFTSs, RSSs, or LTSEs, empirical data are critical for gauging model competence and performance. Below we discuss how Smith et al. (1997) linked soil C models to LTSE data to provide a number of new perspectives on soil C change.

Table 1. A selection of long-term soil experiments that demonstrate a global interest in quantifying the sustainability of managed systems. Experimental details for most of these can be found in Richter et al. (2006b).

Research site	Location	Soil taxa†	Management regime	Date originated	Reference
Park Grass	Rothamsted Research, Harpenden, UK	Paleudalfs	grass cut for hay	1856	Tilman et al. (1994)
Sanborn Field	Columbia, MO	Ochraqualfs	corn, wheat, crop rotations	1888	Brown (1994)
Askov experiment	Askov Exp. Stn., Denmark	Ochrepts, Hapludalfs	various rotations	1893	Schjonning et al. (1994)
Old Rotation	Auburn, AL	Kanhapludults	cotton and rotations	1896	Mitchell et al. (1996)
Bad Lauchstädt experiment	Bad Lauchstädt, Germany	Inceptisols	various crops and fertilizers	1902	Körschens (1994)
Bretton Plots	Alberta, Canada	Boralfs	wheat–legume rotations	1930	McGill et al. (1986)
Calhoun Exp. Forest	Union, SC	Kanhapludults	pine trees on old cotton fields	1957	Richter and Markewitz (2001)
Wooster Tillage Exp.	Wooster, OH	Fragiudalfs	tillage treatments	1962	Dick and Durkalski (1997)
Tamworth Rotation	Tamworth,NSW, Australia	Chromic and Pellic Vertisols	legume–cereal rotations	1966	Holford (1981)
Haryana experiment	Hisar, India	Ustochrepts	millet–wheat rotation	1967	Gupta et al. (1992)
Yurimaguas	Yurimaguas, Peru	Paleudults	corn–bean rotations	1972‡	Smyth and Cassel (1995)
KwaZulu–Natal acidity trials	Natal, South Africa	Plinthic Paleudult	corn	1982‡	Farina et al. (2000a, 2000b)
Long-term Soil Productivity study	25 North American forests	Entisols, Inceptisols, Alfisols, Ultisols, Spodosols, Vertisols	compaction and organic matter effects	1990-1994	Powers et al. (2006)
Grassland Afforestation	Argentina	Hapludols	eucalyptus on grassland	2000	E. Jobbagy (personal communication, 2006)

† Soil Taxonomy suborder or Great Group (Soil Survey Staff, 1998).

‡ Terminated.

Long-term soil experiments provide direct observations for addressing a number of questions about how and why soils change through time. Yet, the fact that LTSEs are relatively rare is suggestive of limitations. The LTSEs are difficult to initiate and sustain over

Table 2. Uses and challenges of five major approaches to the science of soil change.

Approach	Time scale	Uses and strengths	Challenges and limitations
	yr		
Short-term soil experiments	<1–10	field or lab based, experimental control, versatile, short-term processes	extrapolation to larger scales of space and time, reductionist
Long-term soil experiments	>10	field based, direct soil observation, experimental control, sample archive	duration before useful data, vulnerable to loss or neglect, extrapolation to larger scales
Repeated soil surveys	>10	field based, direct soil observation, regional perspective, sample archive	planning and operational details, very few yet conducted, monitoring
Space-for-time- substitution	>10 to >>1000	field based, highly time efficient	space and time confounded
Computer models	<1 to >>1000	versatile, heuristic and predictive, positively interact with all approaches	dependent on observational data

time; they require good organization, data management, and collaboration among scientists of several generations. The LTSEs may be initiated with the best of intentions, but terminated due lack of funding, shifts in research priorities, societal instability, or simply an absence of interested scientists. The LTSEs that are simple and efficient in design may be more likely to survive, compared with complex experiments that require much labor and expense to maintain. Scientific returns from LTSEs during their early years may be few, and attendant cycles of field work, resamplings, and reanalyses may grow to seem unproductive. Long-term studies are susceptible to neglect or abandonment and even productive LTSEs, such as described by Farina et al. (2000a, 2000b) in southern Africa, can be summarily terminated.

Long-term soil experiments face technical challenges as well (Steiner, 1995). Statistical designs of LTSEs are well worth criticism (Loughin, 2006) and sampling soil with precision and accuracy is not easy. Some treatments such as cultivation may eventually compromise the experiment itself (Sibbesen, 1986). The representativeness of LTSEs is not a trivial issue—for example, Debreczeni and Körschens (2003) estimated that 70% of the world's long-term field experiments are in Europe. An web-based inventory of LTSEs (Richter et al., 2006b) indicates that the vast majority test agricultural objectives, and that >50% are on Alfisols and Mollisols, soils with high native fertility with minimal slope. Steiner (1995) even suggested that few long-term experiments test marginal soils due to inherent unsustainability of such studies.

In the late 19th century, many field experiments were launched due to interests in scientific agriculture (Rossiter, 1975), specifically in soil amendments and agronomic practices that improved crop yields and forestalled yield declines. Significantly, several were used for purposes much broader than yield estimation (Leigh and Johnston, 1994). By the 1860s, experiments were being used to estimate NO_3 leaching as a function of N amendment (Goulding et al., 2000). Many 19th century field studies have not survived, such as Boussingault's Alsace Farm in France, but a remarkable number continued to contribute to advancing soil science and sustainability (Table 1).

Examples of the longest term extant studies include Park Grass in England, initiated in 1856 to investigate hayfield response to soil treatments, once called "the most long-term ecological study" by Tilman et al. (1994); the Sanborn Field in Missouri (1888), designed to study sustainability of soil-nutrient supply and productivity of corn (*Zea mays* L.) and wheat (*Triticum aestivum* L.) on newly cultivated prairie soils (Brown, 1994); and the Magruder Plots in Oklahoma (1892), organized to study the conversion of a native prairie soil to cultivation (Webb et al., 1980). Other >100-yr experiments include the Askov Plots in Denmark (1893) and Old Rotation in Alabama (1896), both of which test crop rotations (Schjonning et al., 1994; Mitchell et al., 1996), and Bad Lauchstädt in Germany (1902), used to quantify fertilizer responses (Körschens 1994). The Lethbridge and Breton Plots in Alberta, Canada (1910 and 1930, respectively) test the sustainability of crop production and soil change in semiarid climates at high latitude (McGill et al., 1986), and in Kybybolite, Australia (1919), the effects of crop rotation are quantified on pasture quality, yields, soil organic matter, nutrient availability, and pH (Russell, 1960).

While most long-term agricultural experiments are in the developed world, a number have been ongoing in the developing world for several decades, including in China, India, and Pakistan (Abrol et al., 1997; Tirol-Padre and Ladha, 2006). Some of the most significant are experiments with intensively managed rice (*Oryza* spp.) that evaluate yield declines and soil change (Bhandari et al., 2002; Tirol-Padre and Ladha, 2006).

The oldest LTSE that continues today dates from 1843, the Broadbalk wheat study in southern England (Jenkinson, 1991). Broadbalk is widely known for its data on wheat yields that span >160 yr, but it is perhaps most valuable for the breadth of its contribution to the science of soil and environmental change. Many of its publications have helped shape soil science, including those that have described 100 to 150 yr of change in soil fertility, C sequestration, acidification, N cycling, NO_3 leaching, air pollutant effects, and the persistence of potentially toxic compounds (Leigh and Johnston, 1994; Smith et al., 1997). The Broadbalk study is discussed several times in this review, not only because its record of soil change encompasses nearly all of the Industrial Age, but also because it so clearly demonstrates the wide-ranging application of LTSEs in general.

The objective of this review is to evaluate how LTSEs address three questions that are vital to the quality of human life and the environment, questions that are fundamentally challenging society now and in coming decades. The three questions ask how humanity can:

- double plant production for food in the coming decades, while minimizing adverse effects on soils themselves and the wider environment
- better manage C cycling across the diversity of Earth's soils and ecosystems, thus benefiting soils and diminishing negative interactions with the atmosphere
- establish greater management control over soil-nutrient circulation, nutrient-use efficiency, and water quality.

REVOLUTIONS IN FOOD PRODUCTION

Can Food Production be Doubled within 50 yr, while Minimizing Adverse Effects on Soil and the Wider Environment?

When the Green Revolution was born in Mexico in the 1940s, crop yields in the developing world were low and stagnant. Neo-Malthusian perspectives were widely held, and the potential productivity of Earth's soils were not well understood (McNeil, 1964). The specter of famine drove several teams of scientists, governmental agencies, and private foundations to accelerate yields and production of wheat, corn, and rice in the developing world (Stakman et al., 1967; Conway, 1999). The agricultural intensification focused narrowly on "moving up the yield curve," developing and disseminating high-yielding varieties of wheat, corn, and rice, along with management packages of fertilizers, pesticides, and irrigation (Conway, 1999; Chandler, 1982; Barker et al., 1985).

The resulting increases in crop yields are human achievements among the most impressive in history. In 50 yr, while human population more than doubled (Fig. 1), food production in the developing world more than tripled (Fig. 2). More impressive still, per capita diets across the developing world improved greatly, particularly in East Asia, but also in Latin America and South Asia. Twentieth-century rice yields illustrate the spread of intensive agriculture among eight Asian nations (Fig. 3). The Nobel Peace Prize of 1970 was awarded to a researcher and exponent of the Green Revolution, Dr. Norman Borlaug.

Field experiments were instrumental to the Green Revolution to test crop growth and yields across soils, climates, and management regimes. The experiments continued for more than a few years, and although most are now abandoned, a number of rice studies have matured into some of the world's most important field experiments (Bhandari et al., 2002; Dawe et al., 2000; Dobermann et al., 2000; Olk et al., 1996; Tirol-Padre and Ladha, 2006). These experiments now test sustainability of intensive rice management across two to four decades, results of which have implications not only for several billion Asians, but also for the environmental externalities of >150 million ha of rice fields (FAO, 2005).

One of the best known rice experiments is the Long-Term Continuous Cropping Experiment (LTCCE) in the Philippines at the International Rice Research Institute (IRRI), the Green Revolution's center for rice development (Chandler, 1982). The LTCCE was initiated in the 1960s, explicitly to test the maximum biological potential of rice (Cassman et al., 1995; Olk et al., 1996; Dobermann et al., 2000). The experiment features high-yielding varieties, three rice harvests per year, and carefully managed irrigation, fertilizers, and pesticides. For the first 6 yr in the 1960s, dry-season yields averaged a remarkable 9000 kg ha^{-1}, yields that steadily declined throughout the 1970s and 1980s, down to 6000 kg ha^{-1} by the 1990s (Fig. 4).

The LTCCE declines spurred considerable scientific interest in the soil, especially since the experiment was testing the biological potential of rice. To date, declines are not fully explained, but are taken to be the effects of triple cropping, redox chemistry, and progressive N limitation (Dobermann et al., 2000). Management interventions in 1991, 1993, and 1994 lowered the water table, allowed some soil aeration, and substituted a fallow for a wet-season rice crop, changes that were immediately followed by substantial recoveries in dry-season rice yields (Fig. 4). Such responses to soil-redox cycling present fascinating possibilities for concepts of agronomic sustainability. Soil-N studies by Olk et al. (1996) are examples of significant research that can only be initiated in an LTSE.

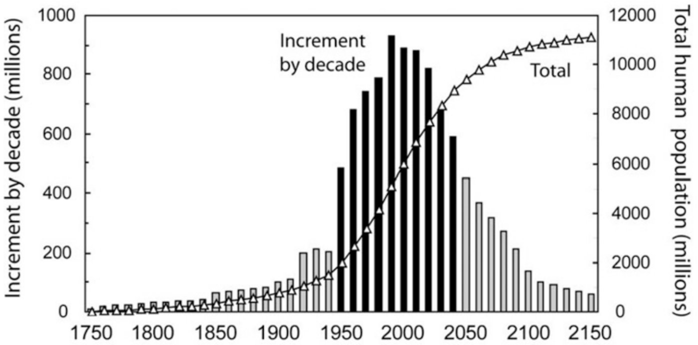

Fig. 1. Decadal increments in human population, 1750 to 2150 (modified from Bongaarts, 1995). Black bars of decadal increments illustrate a most critical 100 yr for human history and for soil science and management as well.

Although rice-yield declines may not be widespread in long-running double-crop rice experiments (Dawe et al., 2000), both meta-analysis and random regression coefficient analysis indicate that rice declines are significant in a number of experiments in South Asia and China, despite high levels of management (Tirol-Padre and Ladha,

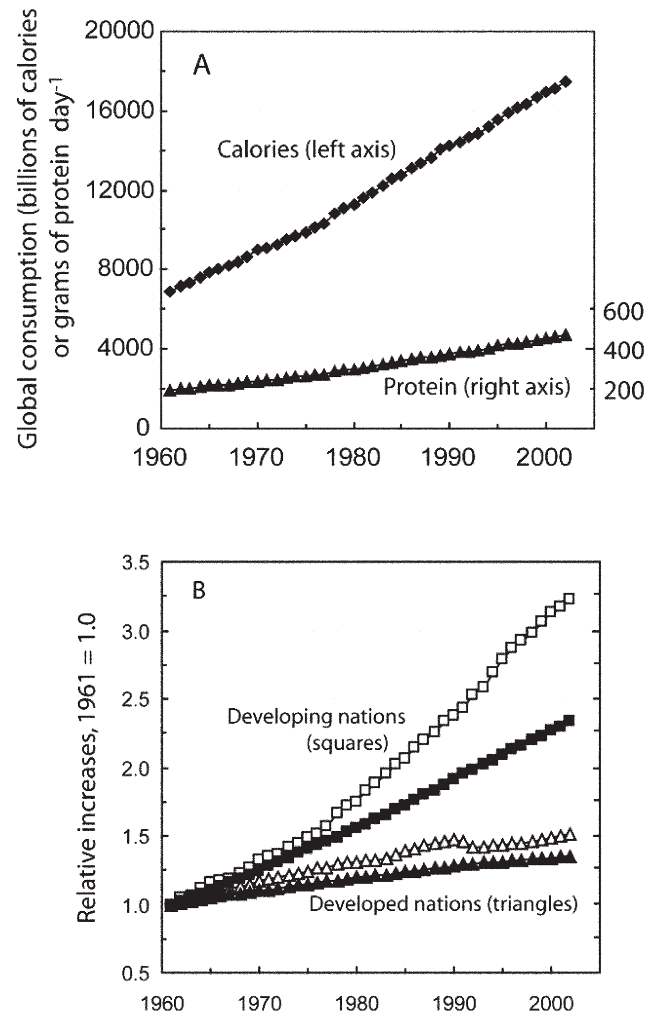

Fig. 2. (A) Global consumption of calories and protein by humanity; and (B) relative increases in protein production (open triangles and squares), compared with relative growth in human population (solid triangles or squares). In (B), the year 1961 is taken to be 1.0 (FAO, 2005).

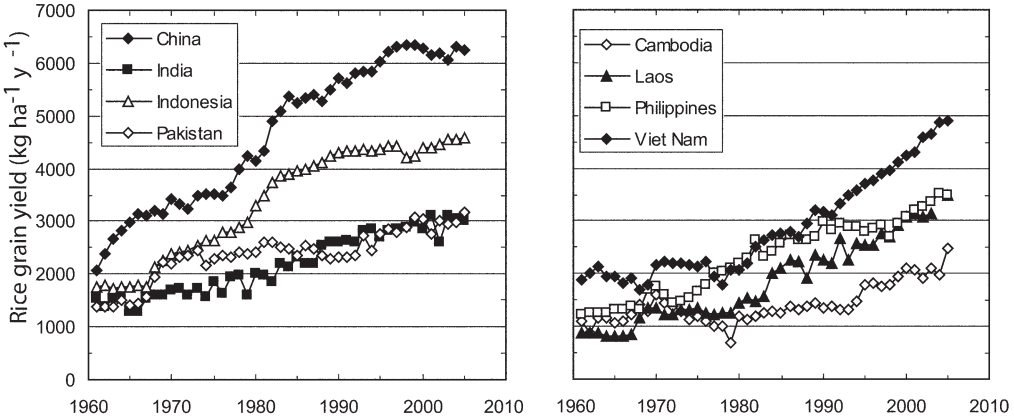

Fig. 3. Trends in eight nations' rice yields, 1961 to 2004 (FAO, 2005). China, Indonesia, Laos, and the Philippines increased yields by threefold or more, India and Pakistan about double. Pakistan is more variable through time; Vietnam has a most impressive takeoff after 1980; and Cambodia has low stagnant yields until the mid-1990s.

2006). In rice–wheat rotations, declines occur in rice but not wheat, declines attributed to changes in soil physical properties, soil toxicities, diminished soil availability of P, S, B, Mn, and Zn, and changes in nighttime temperatures. Much remains to be learned about the sustainability of rice management, and long-term rice experiments present an enormous potential for LTSE research in the years ahead.

In contrast to rice, long-term wheat experiments lack the active networking and cross-site research that exists among rice studies. Nonetheless, the world's oldest LTSE is the aforementioned 160-yr wheat experiment on Rothamsted's Broadbalk Field. Broadbalk's wheat yields have varied enormously between treatments and with time. Yields have ranged between 500 kg ha^{-1} in the unfertilized treatment to 6000 kg ha^{-1} in treatments receiving either inorganic fertilizers or organic manure (Fig. 5). Yields up to 10000 kg ha^{-1} have been attained for wheat immediately after crop rotations (Poulton, 2006). Yield variations depend on management inputs, soil fertility, weather, pests, and weeds (Fisher, 1924; Jenkinson, 1991; Johnston, 1994; Moss et al., 2004). For example, before World War I, Broadbalk was hand weeded for many years, but lack of labor during and after the war made hand weeding impossible, and wheat yields suffered a two-decade decline (Fig. 5). This slide was halted in the 1920s by introducing a fallow with plowing, a regime that continues 1 in every 5 yr (Moss et al., 2004).

Agronomic results from the Broadbalk experiment, like those of the long-running IRRI experiment, greatly stimulated research on soils (Jenkinson, 1991; Johnston, 1994), and demonstrated how sustainability of crop yields depends on management flexibility and interventions and an understanding of the entire agroecosystem, including the soil. Starting in the 1950s, new soil and crop management practices were introduced to all treatments of the Broadbalk experiment. Liming (post-1950), herbicides (post-1960), high-yielding wheat varieties (post-1970), and fungicides (post-1980) together doubled grain yields in fertilized plots (Fig. 5). The doubling of yields has substantially increased demands on the soil's overall fertility, and thus the contemporary Broadbalk study asks fundamentally new questions about the soil–crop ecosystem: What are the physical, chemical, and biological limits and consequences of such intensification? For how long can even the fertile Broadbalk soils support greatly elevated yields? How does intensified management alter soil C, nutrient cycling, and physical–biological–chemical soil dynamics, and externalities as well?

These are the new and highly significant questions for all of 21st-century agriculture. Certainly Broadbalk's specific results will be important to understanding such questions, but the most valuable lessons from Broadbalk may be its ability to demonstrate how well-managed, productive LTSEs can contribute to a broad sweep of questions about soil and ecosystem change.

LTSEs and Future Revolutions of Food Production

Most impressive are suggestions that Earth's soils now produce food in such abundance that feeding humanity has more to do with food distribution than with the soil's ability to produce food (Lappé et al., 1998). In fact, recent approaches to combat malnutrition appear

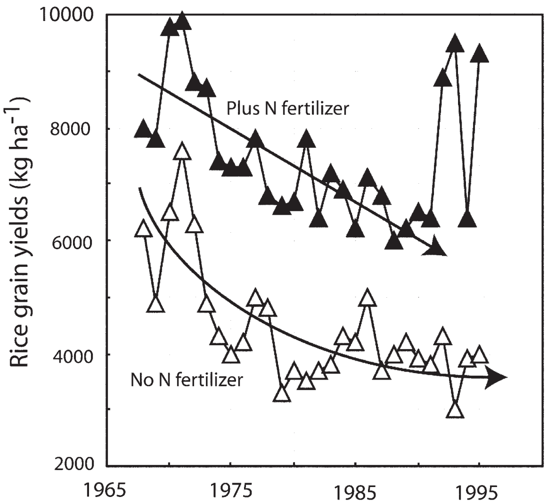

Fig. 4. Dry-season rice yields during 25 yr in two experimental treatments of the long-term continuous cropping experiment at IRRI in Los Baños, Philippines. The treatments are with and without added fertilizer N.

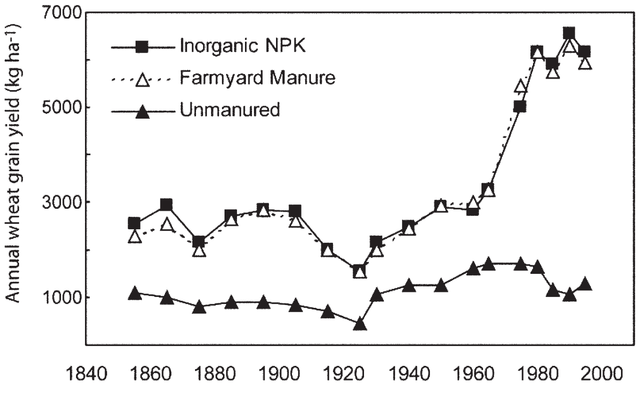

Fig. 5. Wheat yields for >150 yr in three experimental treatments of the Broadbalk wheat experiment at Rothamsted Research, Harpenden, UK. The three treatments are: no fertilizer amendments (unmanured), inorganic fertilizer at 144 kg N ha^{-1}yr^{-1}, and organic farmyard manure that currently averages 240 kg N ha^{-1}yr^{-1}.

to deemphasize food production in favor of improving access to food, health care, sanitation, education, hygiene, and nutritional practices (Sánchez and Swaminathan, 2005; U.N. Millennium Project, 2005).

Such approaches to combating malnutrition make important assumptions about the sine qua non of agroecosystems, i.e., the soil and its sustainability under intensive management. We are, after all, already working Earth's soil at an intensity and geographic scale never before attempted. Of 13 billion ha of soil on Earth, which includes vast deserts, mountain lands, and high latitudes, nearly five billion are cultivated and managed in permanent crops or pastures, with about two billion more periodically logged for wood (FAO, 2005). To suggest that food production be deemphasized underestimates the demands that doubling world food production by 2050 will place on soils and the environmental change that will certainly follow.

Long-term soil experiments have three key roles to play in improving food production and soil management in the coming decades. First, LTSEs can help test new cropping systems that minimize adverse effects on the wider environment (Rasmussen et al., 1998). These LTSEs include those that are ongoing, but new experiments as well. New LTSEs continue to be initiated, experiments that explicitly test crop-yield quantity and quality, soil sustainability, and environmental effects as well (e.g., Tu et al., 2006; Denison et al., 2004).

Second, LTSEs can provide early warning capabilities to detect threats to future crop production (Barnett et al., 1995). Long-term agricultural and forestry experiments serve as leading indicators of sustainability and early warning indicators of yield declines, and give scientists opportunities to investigate factors governing trends in productivity before they are observed in farmers' fields. The IRRI's LTCCE illustrates how declines were discovered in triple-cropped rice (Fig. 4), how researchers responded with process-based studies, and how ideas about rice management and soil change interacted through the agricultural community.

In addition to promoting sustainable increases in crop yields and serving as indicators of crop sustainability, LTSEs have a third role in the coming decades, one that is currently not well developed. The LTSEs can be aimed squarely at boosting soil productivity in regions where hunger is pervasive and soil fertility is in demonstrable decline.

LTSEs and Improved Soil Management in Hunger-Prone Regions

Although the Green Revolution impressively increased crop yields across the developing world, decreasing human malnourishment from 33 to 18% in about 40 yr, the harsh reality is that nearly 900 million people remain significantly undernourished in Africa, Latin America, the Caribbean, and Asia. Our gravest concerns are with sub-Saharan Africa, a region where soil fertility is degraded across enormous areas.

Soil fertility and water management are now recognized as major factors limiting food production in sub-Saharan Africa (Buresh et al., 1997; Hilhorst and Muchena, 2000; Sánchez and Swaminathan, 2005). Nutrient amendments are not used by many farmers, and continued harvests of grains and residues are primary causes for fertility depletions. Because organic matter is also diminished by soil use, the sub-Sahara's sparse and variable rainfall challenges soil management with infertility and drought stress. To help reverse current trends, LTSEs can test and promote simultaneous improvement of yields and soil fertility, and contribute to a larger strategy of agricultural development in the sub-Sahara.

Many LTSEs have historically operated in Africa and the recognition that degraded soil fertility is a main factor limiting agriculture in the sub-Sahara has increased interest in African LTSEs (Bekunda et al., 1997). Even today, however, productive African LTSEs are unfortunately being abandoned, including at least one that provides insight into improving soil fertility in difficult-to-manage acid soils (Farina et al., 2000a, 2000b). Novel agroforestry and water-harvesting techniques might provide a focus to help catalyze a regional network of LTSEs that addresses the twin needs of crop yields and soil fertility (Sánchez and Swaminathan, 2005). Although the task is complex, a network of efficiently run LTSEs could help demonstrate and facilitate agricultural development. Across a range of sub-Saharan management systems, soils, climates, and human–soil interactions, LTSEs could promote what these experiments have long been designed to do: sustainably increase crop yields and quality, and serve as leading indicators of crop, soil, and environmental sustainability.

LTSEs AND THE GLOBAL CARBON CYCLE

Can Humanity Better Manage Carbon Cycling across the Diversity of Earth's Soils?

For most of the last 1000 yr, atmospheric CO_2 varied little and averaged about 280 uL L^{-1}. In about 1800, however, atmospheric CO_2 started increasing—slowly at first and then progressively faster, surpassing about 370 uL L^{-1} in 2000 (Etheridge et al., 1996). The increase is caused by the growing pace of industrial activity, deforestation, and soil cultivation (Houghton, 2003), which together transfer enormous amounts of CO_2 to the global atmosphere (Fig. 6). This fundamental shift in the global C cycle is important to scientists and policy analysts alike, as atmospheric CO_2 affects plant photosynthesis, ecosystem C cycling, and the biosphere's radiation balance as well (International Panel on Climate Change, 2001).

Where Has All the Carbon Dioxide Gone?

Although much remains to be learned, a proliferation of recent C research has advanced our understanding of global C fluxes. Of the CO_2 added by humanity to the atmosphere (Fig. 6), fossil fuel combustion

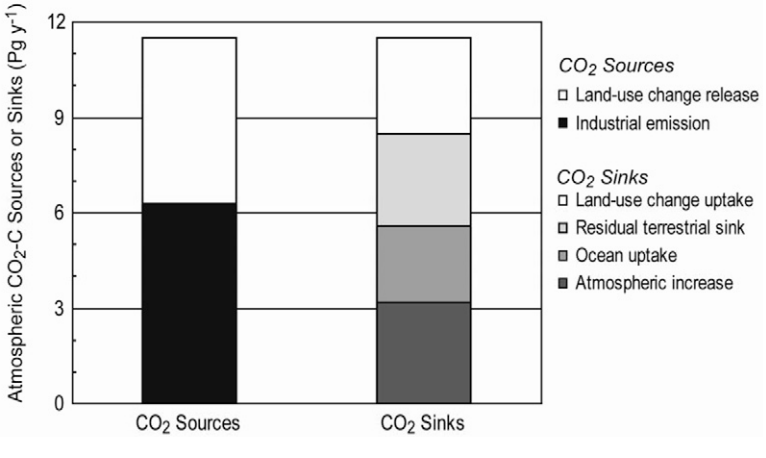

Fig. 6. Global C budgets for the 1990s (Houghton and Goodale, 2004). Based on fossil-fuel combustion and land-use change releases, total sources to the atmosphere were estimated at 11.5 Pg yr^{-1}. Sinks were estimated directly except for the residual terrestrial C sink that is estimated by difference of sources and sinks. Citations are for land-use change release and uptake, and residual terrestrial sink (Houghton, 2003; Houghton and Goodale, 2004; R.A. Houghton, personal communication, 2006); fossil fuel emissions and atmospheric increase (Prentice et al., 2001); and ocean uptake (Plattner et al., 2002).

and other industrial activities account for 6.3 Pg CO_2–C yr^{-1} (Prentice et al., 2001). Land-use changes that include deforestation and soil cultivation also oxidize massive amounts of dead vegetation and soil organic C to CO_2, emissions typically reported as a net release from land-use change (International Panel on Climate Change, 2001), currently estimated at 2.2 Pg CO_2–C yr^{-1} (Houghton and Goodale, 2004). This net release masks the dual nature of land-use change effects on the global C cycle (Fig. 6), that is, that 5.2 Pg CO_2–C yr^{-1} is estimated to be released from ecosystems losing C (e.g., forests converted to agricultural fields), whereas 3.0 Pg CO_2–C yr^{-1} is taken up by ecosystems accruing C in biomass and soil (e.g., abandoned fields growing secondary forests). The global C budget in Fig. 6 divides land-use change into component sources and sinks (R.A. Houghton, personal communication, 2006).

The additions of CO_2 cycle prominently through Earth's biosphere, and especially through terrestrial ecosystems (Fig. 6). Of the 11.5 Pg CO_2–C yr^{-1} released (Fig. 6), 28% accumulates in the atmosphere (3.2 Pg C), 26% is taken up by plant and soil processes in secondary successional ecosystems (3.0 Pg C), 25% cycles into the residual terrestrial C sink (2.9 Pg C), and 21% is taken up by oceans (2.4 Pg C). Figure 6 suggests that about 50% of the modern human-affected releases of CO_2 is being sequestered in terrestrial ecosystems.

Estimates of global C fluxes (Fig. 6) have relatively large uncertainties (International Panel on Climate Change, 2001; Schimel et al., 2001; Houghton, 2003; Houghton and Goodale, 2004), an attribute clearly intended in the title of Ralston's (1979) paper, "Where has all the carbon gone"? Although a number of scientific approaches are being used to constrain the global C cycle (some of which are described in Table 2), LTSEs play a special role in the scientific quest to understand and quantify terrestrial dynamics of the global C cycle. Data of LTSEs are instrumental in estimating land-use changes on C releases and accruals, and in improving model performance (Smith et al., 1997). They may also be important in addressing one of the great scientific mysteries of our age, the residual terrestrial C sink (Fig. 6), previously known as "the missing C sink," still in need of conclusive data.

Long-term soil experiments are not only important to estimating the C cycle, but also to understanding how soils and ecosystems respond to elevated CO_2 and climate change. Below, the results of LTSEs demonstrate their importance to scientific understanding of contemporary C cycles, rising atmospheric CO_2, and global warming.

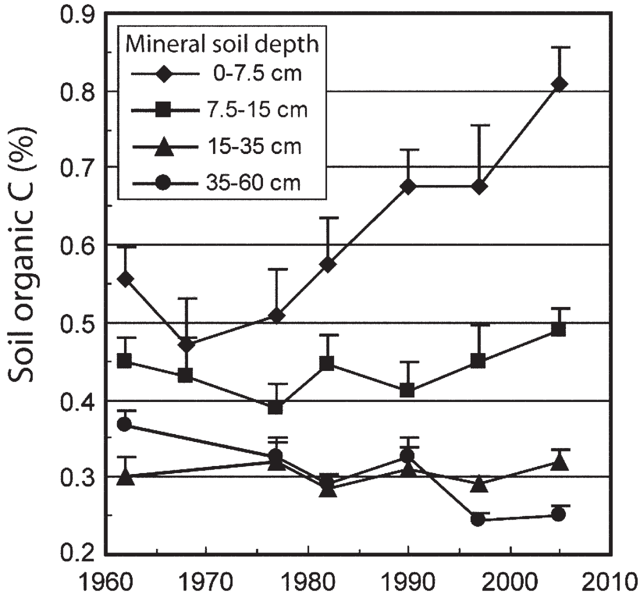

Fig. 7. Mineral-soil C (1962–2005) in old cotton fields planted in 1957 with loblolly pine (*Pinus taeda* L.) seedlings at the Calhoun Experimental Forest, South Carolina (Richter et al., 1999). Error bars depict spatial standard errors among the eight or 16 permanent plots (depending on year of sampling).

LTSEs to Estimate Contemporary Carbon Cycles

To date, LTSEs that directly estimate C accumulations on time scales of decades have not found soils to be a large fraction of the terrestrial ecosystem C sink for C (Richter et al., 1999; Gaudinski et al., 2000; Barford et al., 2001; Schlesinger and Lichter, 2001; Houghton, 2003; Poulton et al., 2003; Bellamy et al., 2005). However, the few whole-ecosystem LTSEs (studies combining plants and soil) that estimate C uptake, can hardly be regarded as presenting a definitive estimate of soil C sequestration worthy of global extrapolation (Clark, 2002). Relatively few forested LTSEs directly estimate decadal-scale changes of above- and belowground C.

One exception is the Calhoun LTSE in South Carolina, which has estimated changes in C above- and belowground during five decades of loblolly pine (*Pinus taeda* L.) forest development, from seedlings to mature trees, all following long-term cultivation of cotton (*Gossypium hirsutum* L.; Richter et al., 1999). In the surficial 30 cm of mineral soil, nearby uncultivated hardwood forests with similar coarse- to medium-textured soils had 40% (1.3 kg m^{-2}) more C than that in the previously cultivated soils now under secondary pine forests (Richter and Markewitz, 2001). To estimate rates of C gains in soil and trees during reforestation (land-use change uptake in Fig. 6), samples were collected periodically from permanent plots, with soil samples archived on seven occasions between 1962 and 2005 (Fig. 7). From an ecosystem perspective, C accumulation has been most rapid in aggrading tree biomass, averaging about 371 g m^{-2} yr^{-1} during the first four decades of forest growth (Richter et al., 1999). The soil, too, accumulated considerable C during the initial four decades of reforestation, with the most rapid accumulations in the surficial forest floor, where 95 g m^{-2} yr^{-1} of C was sequestered in O horizons. Recovery rates of organic C in the previously cultivated upper 15 cm of mineral soil were slower that in the O horizons, and lagged for at least a decade after forest establishment in 1957 (Fig. 7). Despite nonlinearity, between 1962 and 2005, C accrual averaged about 8 g m^{-2} yr^{-1} in surficial layers.

Most studies that estimate changes in soil C focus only on the surface mineral soil. Although the direct estimates of C accrual in Calhoun A horizons demonstrate the value of the Calhoun LTSE, significant losses of C in lower lying layers may be even more instructive. During the same period of reforestation, significant decreases in organic C were observed in upper B horizons at 35- to 60-cm depths (Fig. 7), decreases that amounted to about 10 g m^{-2} yr^{-1} between 1962 and 2005. These decreases are ecologically significant as the C balance in the 0- to 60-cm of mineral soil appears slightly negative between 1962 and 2005 (43 yr of reforestation effected a loss of about 2 g m^{-2} yr^{-1} in the upper 60-cm mineral soil). The decreases in subsoil C are hypothesized to have resulted from slow decomposition of agriculturally derived C in lower lying horizons (Richter et al., 1999). Forests transpire much more water from subsoils than annual crops (Dunne and Leopold, 1978), especially in the warm-temperate climate of South Carolina, thus losses of subsoil C are attributed to greater aeration of B horizons, accelerating net decomposition under trees compared with that under cotton (Richter et al., 1999).

Below 60 cm, soil C dynamics at Calhoun are more intriguing still. In mid- to lower B horizons at 80 and 150 cm, rhizospheres (soil microsites surrounding roots) appear to have accumulated substantial C during five decades of reforestation. For these estimates, soil was analyzed for its organic C and radiocarbon concentrations (Richter et al., 2006c; Fimmen et al., unpublished data, 2006), which in these deep rhizospheres were strikingly more modern than the ancient organic C in surrounding bulk subsoils. Taken together, data on organic C, soil ^{14}C, and volumetric estimates suggest that C accumulated in deep subsoils at >20 g m^{-2} yr^{-1} during nearly five decades of forest growth, an increment of C that has an estimated Δ^{14}C of +32.7‰, in stark contrast with the old soil C found in nonrhizosphere soils of the same depths (Δ^{14}C of −658‰). These data indicate that subsoils can be at least as significant as surface soils in controlling C uptake and release from ecosystems. Results also indicate that our understanding of subsoil C is in great need of improvement.

In research that parallels the Calhoun study, two forests in the United Kingdom accumulated C in old arable soils that had reverted to deciduous woodland during a period of 120 yr at the Geescroft and Broadbalk Wildernesses at Rothamsted (Poulton et al., 2003). Results are in accord with those at Calhoun in that C accumulation was much greater in trees than in soil. In the Geescroft Wilderness, mean rates of C accumulation in litter plus mineral soil to a depth of 69 cm was 38 g m^{-2} yr^{-1}, whereas C accumulation in trees, including roots, was about 162 g m^{-2} yr^{-1}. Unlike the Calhoun results, however, there was no indication of any decline in organic C in the clayey subsoils. The quantity of organic C in the 23- to 26- and 46- to 69-cm layers increased at both Geescroft and Broadbalk forests. At Rothamsted, additional water use by trees seems less likely to increase the decomposition of soil C; in fact, greater drying may slow decomposition. The contrasting dynamics in subsoil C under Calhoun and Rothamsted forests may reflect differences in species, soils, or climates; the results also suggest cross-site studies among LTSEs to explore subsoil C more fully.

Although the Calhoun Forest and the Geescroft and Broadbalk Wildernesses are some of the few forest LTSEs to quantify above- and belowground C accruals, worldwide there are >160 LTSEs across a variety of land uses, a number of which can contribute data on decades-scale C dynamics. Smith et al. (1997) coupled observational C data from seven LTSEs of arable crops, grasslands, and woodlands with nine ecosystem C models and concluded that greater use and linkage of LTSE data and C models would help address questions about soil C that have global significance. The potential for cross-site studies to investigate changes in soil and subsoil C is large.

Repeated soil surveys have recently been used to quantify decadal changes in soil C at regional scales (Bellamy et al., 2005; van Wesemael et al., 2004). Like the Calhoun, Geescroft, and Broadbalk LTSEs, these studies indicate that soil C is rarely at steady state. Bellamy et al. (2005) used a RSS of England and Wales to assess decadal soil-C changes, the first survey accomplished in 1978 to 1983 (McGrath and Loveland, 1992), and repeated at periods 12 to 25 yr thereafter. Management and environmental factors were suggested to influence soil C across different time scales, but overall, soil C decreased in a number of soils during this period, releasing soil CO$_2$ to the atmosphere at rates significant on a large scale. Decreases in soil C were attributed to climate change, management factors such as decreases in grasses within crop rotations, and overgrazing of pastures. Similarly, a RSS in Belgium described soil C change in several agricultural regions, soil-C declines attributed to decreased animal densities, reduced manure inputs in pastures, and more intensive and deeper cultivation (van Wesemael et al., 2004). These two RSS studies illustrate the potential value of repeating soil surveys in operational landscapes; they also illustrate differences with LTSEs, in which management is experimentally controlled. The two approaches are entirely complementary, and should in the future provide insights into soil dynamics at a range of spatial and temporal scales.

And finally, how to examine C dynamics of massive land disturbances without LTSEs or RSSs, for example, of tropical forest deforestation or boreal-zone wildfires that extensively burn Gelisols? While LTSEs might in the future quantify the C dynamics of these disturbances, in the meantime, space-for-time substitutions can be used at least to initially estimate fluxes.

Tropical deforestation has a major impact on the global C budget and since few, if any, LTSEs directly estimate C dynamics following tropical deforestation, Cerri et al. (2003) used a SFTS with 20 sites of differing pasture age in Rodônia, in Brazil's western Amazonia, to indirectly estimate decadal changes in soil and ecosystem C. Forests had been cleared 2 to 88 yr previously and, after establishing soil and climatic similarity among sites, soil C was found to be lower in pastures several years after deforestation, but in long-managed pastures, C was much greater than that in the original forest. Initial soil-C stocks were 3.4 kg m^{-2} to the 30-cm depth under forest, but were >5.0 kg m^{-2} in the 88-yr-old pasture. The pasture's recovery of soil C did not compensate for C lost in trees (>10.0 kg m^{-2}), yet soil C gains were significant to the overall ecosystem C budget.

Boreal-zone forests periodically burned by wildfires release large quantities of CO$_2$ to the atmosphere both during the fires and in the post-fire years by decreasing albedo, warming soil (even melting permafrost), and accelerating soil respiration. Although permafrost-affected Gelisols contain up to a third of the Earth's soil C (Dixon et al., 1994), few, if any, LTSEs estimate decadal dynamics of Gelisol C. O'Neill et al. (2003) used a SFTS with six major wildfires up to 150 yr in age in the Tanana River Valley of Alaska. Soil C appears to reaccumulate slowly in the first decades following fires, due to accelerated decomposition, but thereafter C may accrue at relatively high rates for many decades, at between 30 and 60 g m^{-2} yr^{-1}. Both the tropical and boreal SFTS studies used models to greatly facilitate these investigations.

LTSEs Test Effects of Rising Atmospheric Carbon Dixoide and a Warming Environment

How rising CO$_2$ and temperature interact with soil C and biogeochemical processes is rapidly evolving as a major environmental issue, which remains remarkably unresolved. Dozens of experiments worldwide, not a few of which can be considered LTSEs, are testing the responses of ecosystems to elevated atmospheric CO$_2$ and soil warming. Given the large content of C stored in global soils (>2000 Gt, Bolin and Sukuma, 2000), even small C exchanges between the atmosphere and soil can impact atmospheric CO$_2$ and mitigate or exacerbate global warming. These issues require resolution if we are to advance global-change science and predict future concentrations of atmospheric CO$_2$.

Elevated Carbon Dioxide Effects

The effects of elevated CO$_2$ on ecosystems are tested with chamberless Free-Air Carbon Dioxide Exchange experiments, known as FACE studies. The longest-running FACE studies were initiated in the late 1980s, and the gradual accumulation of FACE data is greatly increasing our understanding of soil, ecosystem, and global-change sciences (Long et al., 2006).

A recent review of FACE studies in four forests with CO$_2$ elevated to about 550 uL L^{-1} indicated that the response of net primary productivity (NPP) to elevated CO$_2$ was remarkably similar: the median stimulation of NPP was 23 ± 2% (Norby et al., 2005). Elevated CO$_2$ in FACE studies accelerates photosynthesis; allocation of photosynthates to roots, rhizospheres, and soil (Pregitzer et al., 1995; Matamala and Schlesinger, 2000; King et al., 2001; Norby et al., 2004; Bernhardt et al., 2006); and overall ecosystem NPP (Norby et al., 2005).

Much of the CO_2–enhanced NPP is allocated belowground to roots (Pregitzer et al., 1995; Matamala and Schlesinger, 2000; Bernhardt et al., 2006), but is ephemeral, cycling rapidly through fine roots, nonwoody roots, and symbiotic fungi. Fine roots and associated rhizosphere biota are important regulators of biogeochemical cycling and their turnover is important to soil C. Most newly allocated belowground C may be respired, but a fraction has the potential to accrue in more long-standing root and soil humic pools.

An example of a FACE experiment maturing to become an invaluable LTSE is in northern Wisconsin. The study tested deciduous forest response to elevated CO_2. Elevated CO_2 stimulated fine-root biomass greatly—from 217 g m^{-2} in controls to 436 g m^{-2} under elevated CO_2 (King et al., 2001; Pregitzer et al., 2006). Elevated CO_2 treatments increased soil respiration by 26 to 39%, depending on sampling date. Soil organic ^{13}C was rapidly affected by elevated CO_2 (Pregitzer et al., 2006), demonstrating the intimate relations between atmospheric CO_2, roots, and soil C. Elevated CO_2 was also incorporated into soil humics generally considered to be recalcitrant (Loya et al., 2003).

Meta-analyses of FACE results detected soil-C accrual even 2 to 9 yr after CO_2 was elevated aboveground (Jastrow et al., 2005). The rate of C accrual in the 0- to 5-cm-depth soil had a median of 19 g m^{-2} yr^{-1} under elevated CO_2 compared with controls. Because the first FACE studies date from the late 1980s, FACE LTSEs will produce critical data in the years ahead.

Soil Carbon in a Warming World

Because temperature is a primary driver of decomposition (Jenny, 1980; Burke et al., 1989; Townsend et al., 1995), global warming's effects on soil C might seem straightforward, especially compared with the interaction of elevated CO_2 and soil C. Indeed, soil-warming LTSEs indicate that elevated temperature accelerates soil respiration and such results create concerns about a positive feedback between temperature and soil C of global significance. A meta-analysis of >12 warming experiments indicates that warming of <3°C increased soil respiration by 20%, net N mineralization by 46%, and plant productivity by 19% in temperate forests, grasslands, and tundra (Rustad et al., 2001).

How warming affects soil C over decades' time is now recognized to be a matter of great complexity. Not only are we challenged to predict future climate, the duration of most soil-warming LTSEs is not yet two decades, and warming treatments that initially respire labile C may, over decades, result in diminished temperature response. Melillo et al. (2002) suggested that because labile fractions of soil C are limited in pool size, temperature effects would be short lived and small in magnitude. Giardina and Ryan (2000) also suggested limited and minor global warming effects on decomposition.

Recent studies, however, have rather forcefully argued that decomposition of slowly cycling organic C may be just as or more temperature dependent than labile fractions (Bosatta and Ågren, 1999; Knorr et al., 2005; Fang et al., 2005; Powlson, 2005). Knorr et al. (2005) and Fang et al. (2005) presented model simulations and experimental results, respectively, with both studies based on LTSE warming studies, and concluded that warming accelerates decomposition of labile and recalcitrant fractions of C. The fact that soil-warming studies initially accelerate CO_2 efflux, which subsequently and quickly returns to prewarming rates, may entirely mask warming effects on recalcitrant fractions of soil C. For even if turnover rates of recalcitrant fractions are much more temperature dependent than labile pools, experiments with relatively short durations can hardly reveal these significant changes (Knorr et al., 2005). Significant feedbacks between soil warming, decomposition, and climate remain an entirely reasonable hypothesis. Jones et al. (2005) linked soil C and climate models, and estimated that a climate–soil–atmosphere feedback might transfer >50 Pg C to the atmosphere in 140 yr, not dissimilar to that simulated by Cox et al. (2000).

Results from LTSEs show how we are taking initial steps toward understanding interactions between soils and the global environment. From this brief review, it is clear that LTSEs are critically important to the future of global-change research.

LTSEs AND NUTRIENT CYCLING

Can Humanity Establish Greater Management Control over Soil-Nutrient Circulation?

Archeologists use soil P to characterize ancient villages and arable fields (Eidt, 1977), thus demonstrating the long-lasting effects of humanity on soil-nutrient cycling. Low solubility makes P a useful marker of historic land use. In recent decades, humanity has transformed cycling of macro- and micronutrients on local to global scales, and in coming decades, management of nutrient circulation will become increasingly important to establish.

The establishment of greater management control over global nutrient capital and cycling can benefit from LTSEs that quantify decadal rates of soil-nutrient retention and recycling, and soil-nutrient release to plants, the atmosphere, and drainage waters. The variety of ways that LTSEs facilitate the understanding and management of nutrient cycling and nutrient-use efficiency is reviewed using N, P, and S.

LTSEs and Soil Nitrogen

Nitrogen-use efficiency (NUE), the fraction of fertilizer N taken up by crops and removed in harvest, averages about 33% for the world's cereals (Raun and Johnson, 1999). In many river basins, N not taken up by plants or retained by the soil leaches into drainage waters, runs off with sediments, volatilizes to the atmosphere, and contributes to eutrophication or hypoxia in aquatic systems (Diaz and Rosenberg, 1995; McIsaac et al., 2001).

Because NUE has a large interannual variability due to the weather (Goulding et al., 2000), LTSEs are well suited to the task of quantifying and increasing NUE on time scales of decades. Many LTSEs can estimate and help increase NUE, and such data are particularly important because sustainably doubling food production in the coming decades will require increasing N uptake and NUE. While the Green Revolution relied heavily on increasing crop N uptake by increasing N inputs, future doubling of crop production is challenged to boost both N uptake and NUE, reducing N released to the environment.

Nitrogen-use efficiency can be increased, a conclusion demonstrated by a number of LTSEs, for example, the 110-yr-old Old Rotation LTSE in Alabama. The NUE of Old Rotation's major treatments ranged from 20 to 70% (Table 3), even when calculating NUE with an estimate of total N inputs. Nitrogen cycling efficiency was greatly affected by climate and management of plants and soil.

Even in the 19th century, when LTSEs mainly estimated crop responses to inputs, they were used to estimate relationships between N amendments and NO_3 leaching. Between the 1840s and the 1880s, both LTSEs and STSEs explored whether manure could be soil applied throughout the year or whether it would best be saved for the growing season when plant N uptake was highest and N loss to leaching minimized (Way, 1850; Johnston, 1994; Goulding et al., 2000). In the 1990s, NO_3 concentrations were much lower in water draining from the same Broadbalk plots and tile drains measured in the 1860s and 1870s, a result ascribed to the much higher N uptake of modern, high-yielding varieties of wheat (Goulding et al., 2000). In this latter study, when N fertilizer was applied in spring to wheat sown the previous fall, leaching was relatively small for N amendments up to those giving maximum crop yield (about 150 kg N ha^{-1}) and only slightly more than that from unfertilized plots (Goulding et al., 2000). Results are corroborated by those from ^{15}N-labeling studies that have shown less N loss when N was applied in the spring than the fall (Powlson et al., 1986a, 1986b) due to improved synchrony of N availability and crop uptake.

Glendining and Powlson (1995) reviewed data from LTSEs worldwide to quantify the long-term impacts of N fertilizers on soil N cycling. Across LTSEs, N applications increased N recycling from crop residues and root turnover and exudates. Initially, these increased inputs influenced mainly labile fractions of soil N, but over years and decades they affected more slowly cycling fractions of soil organic N as well. The LTSEs are well suited to elucidating mechanisms that operate across such time scales.

These examples illustrate well a major use for LTSEs in the decades ahead, for research aimed at improving N-use efficiency and minimizing N loss to the environment.

LTSEs and Soil Phosphorus

The cycling and management of P contrasts with that of N, as P and N cycle through soil with different rates and reactions. Whereas N is associated mainly with organic matter, P is associated with organic matter, Fe- and Al-oxides, and Ca compounds as well. While N has a prominent atmospheric cycle via biological fixation and air pollution, P is largely a terrestrial element, although with notable exceptions (Chadwick et al., 1999). If oxidized to NO_3, N readily enters soil water as a solute, whereas P is generally considered relatively immobile, except when erosion transports particulate-bound P.

Long-term soil experiments are making two major contributions to advancing the understanding and management of soil P. First, LTSEs are demonstrating the ecologic significance of slowly cycling fractions of P, and second, LTSEs are documenting that P may be much more mobile within soils than we have suspected, specifically in soils receiving long-term or heavy inputs of P in fertilizers or organic matter (Hesketh and Brookes, 2000).

A large number of scientific studies that include some assessment of bioavailability of soil P consider only the most labile fractions of P, neglecting entirely lower solubility organic P (Po) and inorganic P (Pi). Soil chemists first described slowly cycling P fractions (Chang and Jackson, 1957; Hedley et al., 1982), and a number of LTSEs now demonstrate the ecological significance and bioavailability of slowly mineralizable Po, Pi associated with Fe- and Al-oxides, and Ca-associated Pi as well (Goh and Condron, 1989; Tiessen et al., 1992; Beck and Sánchez, 1994; Richter et al., 2006a; Blake et al., 2000). Research at LTSEs has developed several quantitative approaches to estimating the bioavailability of slowly cycling P (Schmidt et al., 1996).

In a 17-yr study to examine the bioavailability of slowly cycling P, Schmidt et al. (1996) alternated corn and soybean [*Glycine max* (L.) Merr.] on two Ultisols, added P at four rates for 11 yr, and curtailed P inputs for the subsequent six. Samplings of soil were made throughout, which clearly indicated how plant uptake of P came not only from the most labile P, but also from more recalcitrant Po and strongly sorbed Pi. Remarkably, slowly cycling fractions of Pi and Po are extracted only by extreme chemical treatment, e.g., 16-hr extractions with 0.1 *M* NaOH. The researchers considered the Pi and Po fractions extracted by NaOH to be an important part of the soil's "biodynamic P," a slowly cycling long-term source of P, and even an index of "a potential return on an investment in P fertilizer."

Phosphorus mobility in soils is now an important environmental issue, due in large part to results from LTSEs. Heckrath et al. (1995) reported unexpectedly high P concentrations in drainage waters of long-fertilized Broadbalk soils, and at three European LTSEs, Bad Lauchstädt, Skierniewice, and Broadbalk, 30-yr P budgets suggested significant P leaching from surface soils into underlying layers (Blake et al., 2000). In Wisconsin, P leaching was markedly higher under corn long managed with inorganic fertilizers than in nearby formerly cultivated and fertilized soils that had been converted to tall-grass prairie about two decades before (Brye et al., 2002). Much remains to be learned about management and process control over P leaching. Although P is well known to be leachable in fertilized sands or organic soils (Duxbury and Peverley, 1978), preferential flow paths appear to be the active conduits for mobile P in heavily fertilized, fine-textured soils (Hesketh and Brookes, 2000; van Es et al., 2004). Although soluble P may be attenuated after drainage from root zones, P in drainage waters may remain elevated for decades after P fertilization is curtailed (Brye et al., 2002).

LTSEs and Atmospheric Sulfur

Throughout the 1950s to the 1980s, S oxide pollutants greatly affected European and North American atmospheres, as industrial emissions grew more rapidly than their control. Similar phenomena occur in industrializing regions of the developing world today. Pollutant SO_2 is transported hundreds to thousands of kilometers downwind of industrial emissions, where S is deposited and oxidized to H_2SO_4, potentially effecting substantial acidification in poorly buffered soils (Hüttl and Bellmann, 1998).

Table 3. Six-year N budgets for five cotton systems in Old Rotation in Alabama (Mitchell et al., 1996). Nitrogen use efficiency (NUE) ranges between 20 and 70% of N input, even accounting for full N input from fertilizer, N_2 fixation, and atmospheric N deposition.

Cropping system	N inputs from		N in crop harvests	NUE†
	Legumes	Fertilizers		
	kg ha^{-1} (6 yr)$^{-1}$			%
Continuous cotton with no N inputs	0	0	72	–
Continuous cotton with N fertilizer	0	720	240	32
Continuous cotton with winter legume	696	0	228	31
Cotton–corn rotation with winter legume	692	0	238	33
Cotton–corn rotation with winter legume and N fertilization	692	716	280	19
Cotton–corn–soybean with winter legume and winter rye	640	120	550	70

† Additional N input is derived from atmospheric deposition, which totals about 30 kg N ha^{-1} per 6-yr rotation. Nitrogen-use efficiency is expressed as a fraction of total N input (legume, fertilizer, and atmospheric deposition). Seed cotton yields averaged 930, 1860, 2230, 2290, 2560, and 2240 kg ha^{-1} yr^{-1} for the six cropping systems, respectively.

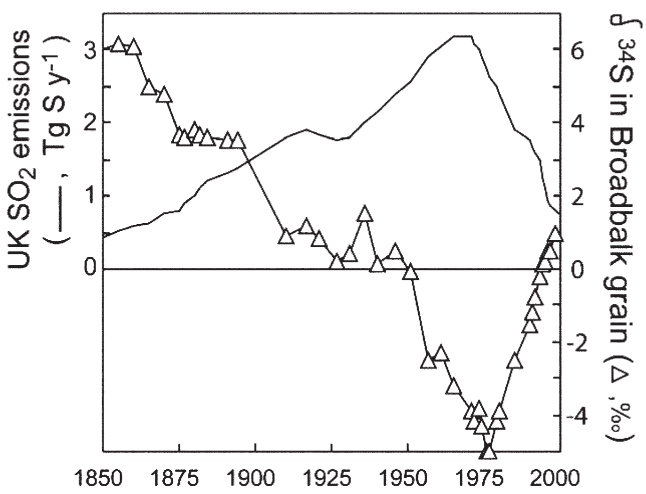

Fig. 8. Wheat grain $\delta^{34}S$ from Broadbalk control plots compared with annual emissions of SO_2 from the UK.

The rate at which air pollutants acidified nonagricultural soil proved difficult to quantify, due in part to a notable absence of LTSEs. Not only are acid-neutralizing reactions poorly quantified (Johnson and Lindberg, 1992), but acidification models, semiquantitative concepts, and short-term experiments (Driscoll and Likens, 1982; Richter et al., 1983; Reuss and Johnson, 1986; Lindberg et al., 1986; Likens et al., 1992) were not able to be compared with direct observations of soil acidification from LTSEs. Ironically, the intimacy with which soils are associated with atmospheric processes has been well demonstrated by a number of LTSEs (Johnston et al., 1986; Markewitz et al., 1998; Zhao et al., 2003, Palmer et al., 2004), two of which are described here.

In ecosystems receiving pollutant S deposition, S circulates between plants and soil, excess S incorporated into organic matter, and SO_4^{2-} adsorbed to soil oxides and leached from soil (Johnson and Lindberg, 1992). Long-archived plant and soil samples at Rothamsted document pollutant effects on S cycling from nearly the birth of the Industrial Revolution. The isotopic composition of S in English coals was estimated to average −10‰ $\delta^{34}S$, which is greatly depleted in ^{34}S relative to soil organic S, estimated in Rothamsted's archived soil from 1865 to be about +8.2‰ $\delta^{34}S$ (Zhao et al., 2003). The rise and fall of S pollution during the 19th and 20th centuries in southern England is illustrated well in Fig. 8, complete with a relatively short lag time between air, plants, and soils, due to the cycling of residual pollutant S through the ecosystem.

Decadal effects of S pollution control are recorded also in soil-water chemistry of an LTSE at Hubbard Brook Experimental Forest in New Hampshire (Palmer et al., 2004). Soil water from three Spodosols was collected for 14 yr, from 1982 to 1998, when atmospheric S was being reduced across eastern North America. Declines in solution SO_4 were significant in all three soils—declines accompanied by decreases in solution base cations in Oa and Bs horizons. At two of three sites, increases were observed in solution acid-neutralizing capacity and decreases in inorganic monomeric Al. Reductions in SO_4 deposition effected little change in drainage-water pH, due to effective pH buffering of soil waters, probably controlled by Al hydrolysis and deprotonation of weak organic acids. Such long-term observations greatly facilitate modeling and strengthen interpretations of short-term experiments.

CONCLUSIONS

Strong irony permeates our era's thinking about soil and ecosystem sustainability. On the one hand, the scientific community seems of one mind in recognizing the importance of ecologically sound soil management. Yet, with notable exceptions, this community has yet to marshal the organization and resources needed to substantiate the scientific meaning of sustainable soil management, an effort to which LTSEs can uniquely contribute. In a world that is required to double food production in a few decades, all while diminishing adverse effects on the wider environment, it is incumbent on us to get the most from LTSEs already under way, promoting reviews, cross-site research, and meta-analyses of topics such as long-term trends in agronomic and silvicultural yields (Tirol-Padre and Ladha, 2006; Dobermann et al., 2000), C cycling and sequestration (Smith et al., 2000; Jastrow et al., 2005), NO_3 and P leaching (Goulding et al., 2000, Blake et al., 2000), management effects on assemblages and functions of soil biota (Hendrix et al., 1986; Holland and Coleman, 1987), P fractions and chemistry (Schmidt et al., 1996; Richter et al., 2006a), micronutrient bioavailability, and soil architecture, drainage, and aeration.

Although it may be understandable why some scientists are reluctant to initiate new LTSEs (e.g., Stone, 1975), it can hardly be denied that during the next 50 to 100 yr, an understanding of long-term soil trends is required if soils are to be managed in ways that sustain their full range of functions. In the past, LTSEs have demonstrated their ability to provide important data and guidance to improve soil management. In the future, LTSEs can expand our understanding of interactions between soil management and the wider environment, and enlighten policy and regulatory frameworks. A key to achieving these goals is to comprehensively inventory and review the long-term soil research base, and to establish an international network to scientifically address the many critical issues that involve soil management and global soil change.

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