REVIEW: AGROECOSYSTEM

Long-Term Agroecosystem Experiments: Assessing Agricultural Sustainability and Global Change

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Long-term agroecosystem experiments can be defined as large-scale field experiments more than 20 years old that study crop production, nutrient cycling, and environmental impacts of agriculture. They provide a resource for evaluating biological, biogeochemical, and environmental dimensions of agricultural sustainability; for predicting future global changes; and for validating model competence and performance. A systematic assessment is needed to determine the merits of all known experiments and to identify any that may exist in tropical and subtropical environments. The establishment of an international network to coordinate data collection and link sites would facilitate more precise prediction of agroecosystem sustainability and future global change.

Sustainable agriculture is not a luxury; when an agricultural resource base erodes beyond a certain point, the civilization it has supported collapses or changes dramatically (*1*). Productive, well-managed agroecosystems currently supply the bulk of humanity's food and fiber, but are they capable of feeding the 8 to 11 billion people that are projected to inhabit Earth in 2050 (*2*)? There is a growing worldwide perception that present trends in agricultural production are neither sustainable nor environmentally sound (*3*). Yield of major crops such as wheat is no longer increasing at the rate it once was (*4*), and excessive soil erosion remains an ever-present threat to sustained crop production (*5*). Potential climate change associated with increasing atmospheric CO_2 (*6*) may intensify the problems of sustainability. Many aspects of the global environment are changing at an unprecedented pace, for example, the increasing threat of atmospheric contaminants such as heavy metals and hazardous organic compounds (*7*). Continued population growth will exert greater pressure in the future on maintaining biodiversity and natural ecosystems (*2*). We will need the best tools available to reliably predict our future in the next century.

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Long-term agroecosystem experiments (LTAEs) exist in many countries of the world and make up the largest temporal and spatial database presently available for determining the impacts of ecosystem change. They provide one of the few means to measure sustainable management systems in agriculture. They can supply information on past change to better predict future effects, but are the data sufficient and reliable? Can we distinguish between natural and anthropogenic ecosystem shifts? Are conventional agricultural practices sustainable, especially if we are in a changing climate? We urge a thorough, systematic identification of all LTAEs and establishment of new experiments in selected ecosystems if needed. The formation of an international network to set protocols for LTAE management and data interpretation may be invaluable for accurate projection of future global change.

Long-Term Agroecosystem Experiments

Agroecosystem experiments were first initiated in the mid 1800s when knowledge of plant nutrition and chemical reaction in soil was in its infancy. Most were not started with longevity in mind but rather to answer simple questions about the nutrient requirements of crops (*8*). The oldest functioning LTAE was started by J. B. Lawes and J. H. Gilbert in 1843 at Rothamsted. Experimental Station in England (*9*). Although many other LTAEs were initiated in the late 19th and early 20th centuries, most did not survive. Practically all exceeded 1 ha in size and required substantial labor and money to maintain. Those existing today were well designed at inception and carefully managed over the years by dedicated individuals. They survived climatic catastrophe, pest and disease attack, political turmoil, war, and scarcity of funds and labor without critical loss of continuity in conduct or experimental measurements.

Any LTAE of more than 50 years duration is described as classical (*10*). In addition to Broadbalk and Park Grass at Rothamsted, a partial listing of other classical LTAEs includes Morrow (1876) and Sanborn (1888) in the United States; Askov (1894) in Denmark; Eternal Rye (1878) and Static Fertilizer (1902) in Germany; Rutherglen (1913), Longerenong (1917), and Waite (1925) in Australia; Skierniewice (1923) in Poland; and Lethbridge (1911) and Breton (1930) in Canada (*10–12*). Most LTAEs are located in stable developed nations, with few found in tropical climates and developing countries (*13*).

Several projects were initiated in the past decade to evaluate the use of LTAE data for measuring agricultural sustainability and environmental change (*14–16*). This evaluation resulted in an increase in the estimated number of LTAEs from less than 30 to more than 240. No one presently knows the exact number of LTAEs. It is essential to evaluate newly identified LTAEs to determine if they have a documented record of management (including accidents and mistakes) and a properly managed soil and plant archive. There is presently no assigned international organization to develop validation protocol.

The Sustainability of Agriculture

Most long-term (>50 year) studies indicate that crop productivity is rising with the adoption of new varieties and appropriate management inputs and appears sustainable (*17*). The effects of technology (improved weed control, disease suppression, and crop varieties) on yield at Rothamsted are highly visible (Fig. 1A) and confirmed by long-term yield trends (Fig. 1B). However, the recent attempt of a Rockefeller Foundation study to identify trends in worldwide agricultural sustainability produced less well-defined conclusions (*18*). Studies of short duration (20 to 40 years) produced fewer positive indications of sustainability than did longer term studies. The former were, however, generally located in humid tropical environments where soil quality changes much more rapidly and ecosystems tend to be more fragile. These disparate findings highlight the need for comparable experiments over a wide range of ecosystems to accurately interpret trends on an international scale.

Soil organic matter (OM) is perhaps the most important determinant of soil quality and is most commonly estimated by determining the soil organic carbon (C) content (*19*). Critical levels of soil C are difficult to establish because they vary with soil texture and climatic regime. Soil C may be less than 1% in some stable soils, whereas other soils would face structural collapse at such levels (*20*). Soil C responds only gradually to changes in agricultural management such as crop rotation, fertilizer input, manure application, or tillage. Most soil C changes require at least 20 years to be detectable by present analytical methods because of the small yearly inputs of C into a much larger matrix, a substantial portion of which is relatively inert.

The tight linkage between crop productivity and soil C change has been a unifying theme in subhumid and semiarid temperate environments (*21, 22*). Trends in Missouri and Oregon in the United States and in Australia (Fig. 2) are representative of changes in most temperate and subtropical climates. Inputs such as manure and mineral fertilizer that have increased crop yield have also increased the amount of crop residue (*23*) produced per hectare. Returning higher amounts of crop residue to soil has an increasingly positive effect on soil C content. Returning residue to soil rather than removing it since the 1950s has converted many soils from "sources" to "sinks" for atmospheric CO_2 involved in global climate exchange (*21, 22, 24*).

Removing a major portion of crop residue tends to reduce soil C content in some climatic environments but not in others (*15, 25*). Belowground C inputs from roots and root exudates appear to be sufficient to maintain soil C in cool humid climates but not in warm tropical or temperate semiarid environments. Belowground material makes up a substantial portion of net annual production in most crops, approaching nearly 40% in modern wheat varieties (*21*). Returning crop residue to soil rather than removing it for other uses is common in stable developed nations but not in developing countries.

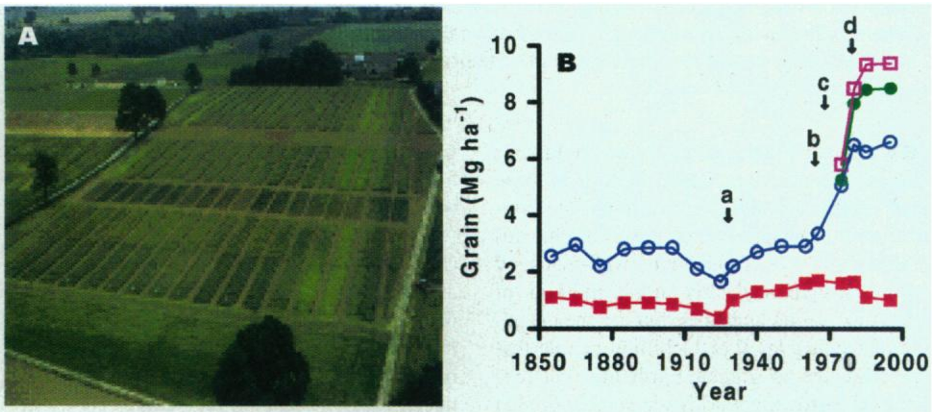

Fig. 1. (**A**) Aerial view of the Broadbalk experiment established in 1843 at Rothamsted, Harpenden, Hertfordshire, United Kingdom. Vegetative differences produced by long-term agricultural management practices are readily apparent. (**B**) Long-term winter wheat yield on Broadbalk in relation to fertility input. Treatments: ■, phosphate (P) and potassium (K) fertilizer applied as needed, no nitrogen (N) fertilizer or farmyard manure (FYM), wheat grown every year; ○, P and K as needed + 144 kg of N ha^{-1} since 1852, wheat grown every year; ●, P and K as needed + 144 kg of N ha^{-1} for wheat grown in a five-course rotation (3 years of wheat, 1 year fallow, and 1 year of potatoes); and □, PK as needed + 96 kg of N ha^{-1} + 13.5 tons of FYM ha^{-1} (moist-weight basis), wheat grown in a five-course rotation. Arrows indicate major changes in management: (a) periodic fallowing (1 year in 5) to achieve better weed control, (b) chemical herbicides applied to control weeds, (c) improved semidwarf wheat varieties planted, and (d) fungicides applied to control foliar wheat diseases. Standard errors of determination: ■, 1882–1927 = 0.11, 1928–63 = 0.12, 1964–78 = 0.19, and 1979–96 = 0.17; ○, 1882–1927 = 0.25, 1928–63 = 0.26, 1964–78 = 0.42, and 1979–96 = 0.41; ●, 1979–96 = 0.59; and □, 1979–96 = 0.60. Refer to (*9*) for more detailed information.

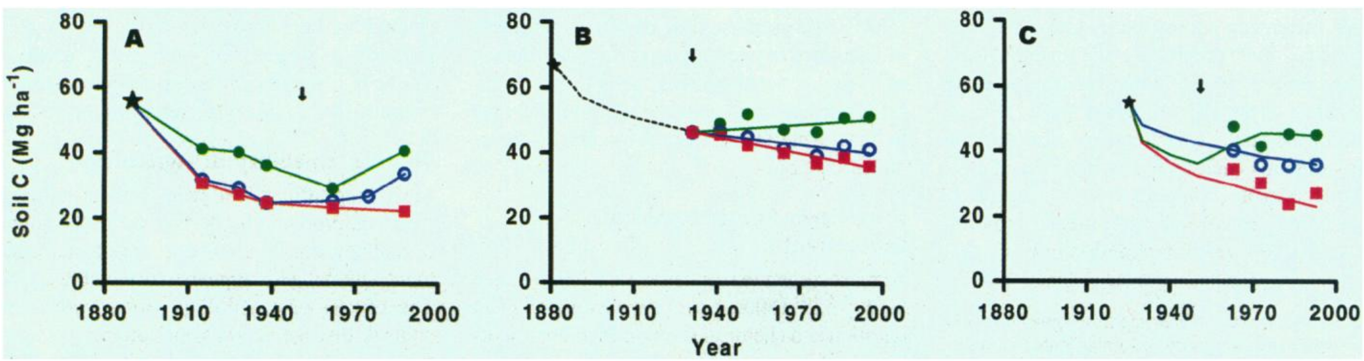

Fig. 2. Crop management effects on soil quality. (**A**) Sanborn Field, Columbia, Missouri, United States, 23-cm soil depth, continuous wheat. Management treatments: ■, no additions; ○, mineral fertilizer; and ●, FYM, 13.5 tons ha^{-1} $year^{-1}$ (moist weight). Arrow indicates change in management; crop residue was removed before 1950 but returned to soil thereafter. (**B**) Pendleton Residue Management experiment, Oregon, United States, 30-cm soil depth, winter wheat grown in a two-course rotation (1 year fallow, 1 year of wheat). Treatments: ■, crop residue incorporated, no fertilizer; ○, crop residue incorporated, inorganic fertilizer applied; and ●, crop residue plus 10 tons ha^{-1} (fresh weight) FYM incorporated. Dashed line is estimated rate of change from 1881 to 1931. The arrow indicates the year that the experiment was initiated (1931). (**C**) Waite Permanent Rotation experiment, Urrbrae, South Australia, 23-cm soil depth. ■, 2-year wheat-fallow rotation; ○, continuous wheat; and ●, 6-year two wheat–four pasture (2W4P) rotation. The arrow indicates the year that 2W4P treatment was initiated (1951). Solid lines indicate the trend predicted by the Rothamsted C model. The (A) and (C) experiments have unreplicated treatments, and the (B) experiment has two series with two replicates. The coefficient of variation (CV) for analytical precision is 3.1, 3.4, and 3.5% for (A), (B), and (C), respectively. The CV for field variability in (B) is 5.9%. Stars indicate C content at time when first cultivated. (A) Printed with permission of Blackwell Science Limited; (C) printed with permission of CAB International. Refer to (*12, 21*) for more detailed information about the experiments.

Sustainability in developing countries may be placed at increased risk when partial adoption of modern technology conflicts with strongly established customs. The benefit of returning a portion of crop residue to soil to maintain OM conflicts with the present practice of removing practically all residues for animal feed, fuel, or bedding. Widespread adoption of mechanized agriculture that promotes more intensive tillage accelerates soil OM oxidation and predisposes soils to increased erosion. If socioeconomic constraints prevent concurrent adoption of residue return to soil, degradation of soil quality and loss of sustainability may result from selective adoption of technology.

In general, most LTAEs can identify management practices capable of maintaining crop yield and soil quality. A combination of inorganic fertilizer and organic manure has given the best yields in many parts of the world (*26*). An optimal combination of organic and mineral fertilizers increased crop productivity in continental Europe by 7% over the use of mineral fertilizer alone (*27*). In the nutrient-poor soils of Australia, a shift to longer crop rotations, particularly the inclusion of pasture leys and elimination of bare fallow, improved the water-stable aggregation of red-brown earth soils. Water infiltration increased, runoff and erosion were reduced, and crop yield increased by up to 40% over traditional wheat-fallow cropping (*12*). In Zimbabwe, no-till ridging increased crop yield up to 17% over traditional methods while reducing soil loss from greater than 4 to less than 1 ton ha^{-1} $year^{-1}$ (*28*). In semiarid and subhumid regions of the United States, elimination of stubble burning, longer crop rotations, less tillage, and greater use of fertilizers and manure improved soil OM content and quality (*21, 22*).

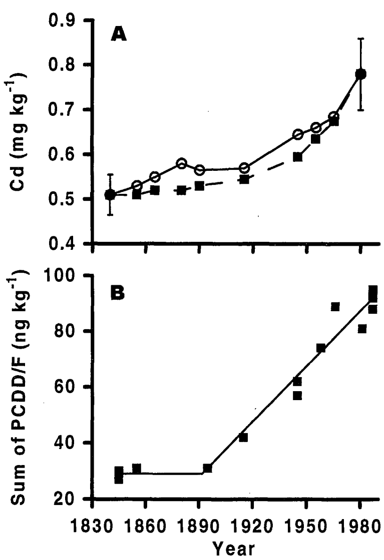

Fig. 3. Long-term change in (**A**) cadmium (Cd) and (**B**) polychlorinated dibenzo-*p*-dioxins and furans (PCDD/Fs) in soil at Rothamsted, United Kingdom, resulting from atmospheric deposition. Data were obtained by analysis of stored soil samples from the Rothamsted archive. For Cd, the open circles are the measured data and the solid squares are the predicted concentration based on assumed global emissions. Error bars for 1846 and 1980 Cd data points are derived from eight separately digested samples. Refer to (*37*) for a detailed discussion of changes in heavy metal and organic contaminant content in soil in relation to industrial and agricultural pollution of the atmosphere.

Long-term experiments show that heavy reliance on ammonium- or urea-based nitrogen (N) fertilizer intensifies soil acidity (*29*), which has numerous detrimental effects on soil quality. Acidification reduces faunal and floral diversity, affects soil-born pathogen activity, retards nutrient cycling, and can restrict water infiltration and plant root development (*8, 30, 31*). Greater soil acidity enhances the mobility of some heavy metals (lead, zinc, and cadmium) and increases the potential for contamination of surface water and groundwater (*30*). The 142-year-old Park Grass Experiment at Rothamsted presently has soil pH values ranging from 3.7 to 7.5 as a result of management, which has produced major differences in botanical composition of grass swards (*31*).

Soil pH is affected by management practices even in semiarid regions, where soils are normally alkaline. Legume-wheat rotations in Australia acidified soil through N fixation to the extent that legume growth could no longer be maintained without regular liming. Heavy reliance on ammonium-based N fertilizers in the Pacific Northwest, United States, to attain optimum yield has progressively acidified near-neutral soils to the extent that liming is required. Increasing acidity on a sandy loam soil at Woburn in the United Kingdom from continued use of ammonium sulfate fertilizer without liming, coupled with a severe cereal cyst nematode attack, resulted in nonsustainable barley yields. In some respects, the failures to ensure sustainability that are identified by LTAEs are as valuable as the successes, provided that the reasons for failure are understood and farming systems are appropriately modified (*8*).

Carbon Sequestration and Global Change

Modeling is considered a reliable method for predicting future events, but models are only as good as the data on which they are based. Modeling biological systems requires reliable data from long-term experiments because short-term changes are often only a part of much longer cycles related to climatic or environmental shifts. An excellent example of the use of LTAEs in this context is found in research on C sequestration and global change. The large size of the soil OM pool (1500×10^{12} kg of C in soil, twice the amount of CO_2-C in the atmosphere) makes it an important component of global C cycling (*6, 32*). Increased C sequestration in soil OM is a possible sink for excess CO_2 and, therefore, a means of ameliorating climate change (*32*). The Global Change and Terrestrial Ecosystem (GCTE) project brought together the major C transfer models to predict effects of increased atmospheric CO_2 on C sequestration in soil and its impact on global climate change (*25*). Model performance was assessed with long-term experiments from diverse climates, soils, and vegetation (*33*). An agroecosystem carbon-pools study in North America (*15*) also evaluated the capacity of soil to sequester C. Soil samples were collected from 32 locations in the United States and Canada and analyzed by specific procedures to measure location and time effects on C and N turnover. Guidelines are now emerging to identify cropping systems that improve C sequestration in soil (*15, 24, 34*). A more unusual use of LTAE data included calculating what effect the plowing up of all old pasture and planting of new pasture for cattle to eradicate bovine spongiform encephalopathy (mad cow disease) would have on C stocks and global CO_2 budgets (*35*). Although the effort was probably unnecessary, it does emphasize the benefit of having research data available to assess rapidly emerging problems and quickly respond to public outcries for a solution. LTAE data may also be used in the future to estimate C change with reforestation or development of managed pulpwood plantations (*36*).

Unforeseen Benefits

Although the original purposes of LTAEs were to define the immediate effects of crop management on yield and SOM, an increasing number of unforeseen uses and functions have been derived from them in recent years. This involved both the interpretation of existing data and the analysis of archived samples. Examples include the following:

1) Analysis of archived plant and soil samples from long-term experiments at Rothamsted identified trends in atmospherically deposited contamination over time (*37*). Long-term trends in cadmium and polychlorinated dibenzo-*p*-dioxins in surface soil are shown in Fig. 3. Most of these soil samples were collected and properly archived before the technology had been developed to detect these compounds and before we were concerned about their buildup in the environment.

2) Analysis of archived soil samples from several LTAEs, for example, Sanborn and Rothamsted, related changes in soil Cd content to background Cd impurities in various phosphate fertilizer sources. This permitted estimates of Cd contents in edible plants and the associated threat to human health associated with continued application of some rock phosphate fertilizer materials (*38*).

3) A soil sample collected from the un-

treated plot growing Timothy grass in the Sanborn experiment in Missouri contained *Streptomyces aureofaciens*, from whence the antibiotic Aureomycin was formulated (*39*).

4) Rigorous experimental design and statistical analysis of time series data sets were developed with data from the long-term experiments at Rothamsted. Statistical techniques and procedures developed by Ronald Fisher and others in the 1930s are still in use today (*40*).

What Does the Future Hold?

Figure 4 represents our interpretation of progressive shifts in the function and purpose of LTAEs over the past 150 years and implications for future use. Conclusions based on 10 to 20 years of data can be very different than those based on 50-plus years of data (*8*). Sustainability, environmental quality, and species-adaptation impacts were never envisioned by the founders of classical LTAEs. Current technology is continually expanding our capability to measure and monitor chemical or biological components that were not possible to measure two or three decades ago. Future analysis of properly archived plant and soil samples from LTAEs can show trends and provide measures of effectiveness for preventative actions.

Agriculture research has, in the past, been fragmented, production-oriented, and territorial. Consequently, research information has not been widely disseminated, and agricultural scientists have had few interactions with other disciplines. This situation is changing, however, as evidenced by coordinated international efforts to define trends in agroecosystem sustainability and CO_2 sequestration in soil by groups such as the GCTE soil organic matter network (SOMNET) and the U.S. Environmental Protection Agency project (*15, 16*). International research organizations such as the Consultative Group for International Agricultural Research, the Food and Agriculture Organization of the United Nations, the International Union of Forestry Research Organizations, and the International Union of Biological Sciences are developing programs in agricultural sustainability and global climate issues (*16*). Networks of LTAEs representative of a wide range of environments are crucial for making regional projections regarding agricultural sustainability and impacts of global climate change (*41*). Each network must include husbandry systems representative of most soils and climates and reflect the dynamics of major ecosystems over relatively long time periods (*42*). Unidentified LTAEs in tropical and subtropical climates need to be located and validated because these regions are presently underrepresented (*13*). It may be necessary to initiate new experiments in developing countries where population is increasing rapidly, as their increasing need for food and fiber will require either more intensive use of existing cropland or greater conversion of forest to cropland. Well-managed LTAEs have a vital role in such programs; we need continuity with the past to better predict the future.

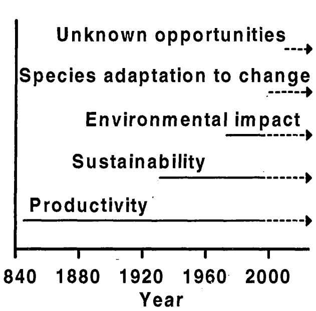

Fig. 4. Changes in the role of LTAEs over time.

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19. Soil quality has proven difficult to define and measure. Most scientists working on this subject prefer multiple measures that reflect the many physical, chemical, and biological (living and dead) components that make up a "healthy" soil. However, soil OM strongly influences many soil properties (structure; air-, water-, and nutrient-holding capacity; resistance to erosion; compaction; and so forth). A soil that has been managed to maintain or increase its OM content is likely to be of better quality than one in which OM has been allowed to decline. Most scientists measure organic C in soil and plant tissue because there are no reliable methods for measuring OM content. Carbon can be determined with high precision and accuracy. Soil OM contains about 58% C and most plant tissue about 42% C, by weight. Soil OM is, therefore, traditionally estimated by determining its C content and multiplying this value by 1.72. Inorganic C can exist in appreciable amounts in arid and semiarid soils, primarily as $CaCO_3$. Any estimate of soil C in this paper that includes inorganic C is so identified.
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