Overview of Long-Term Agronomic Research

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ABSTRACT

Renewed interest in low-input and sustainable crop production has rekindled interest in long-term agronomic research. Research plots that have been monitored continuously since the late 19th Century exist in several states. Twenty-five experiments have been identified that have been monitored for over 25 yr; 12 of these are more than 50 yr old. Yield and treatment records provide valuable information on the effects of cropping systems, tillage, manuring, and fertilization practices on yields and on soil physical and chemical properties. Most of these very early tests were non-replicated studies using large plots and crop rotation systems. Four of America's oldest, continuous agronomic research tests were reviewed in more detail: (i) Illinois' "Morrow Plots" (c. 1876), (ii) Missouri's "Sanborn Field" (c. 1888), (iii) Oklahoma's "Magruder Plots" (c. 1892) and (iv) Alabama's "Old Rotation" (c. 1896). All of these are listed on the National Register of Historical Places. These studies document that long-term crop production can be sustained and improved in different regions and on different soils of the USA. Long-term studies have shown that crop rotations and attention to recognized and established soil fertility practices, which may or may not include legumes and manuring, are essential to maintaining high, sustained production.

THE MORRILL ACT of 1862 created the Land Grant colleges to teach agriculture and the mechanical arts. It provided funds for buildings, classrooms, and salaries but made no provisions for developing appropriate subject matter to teach students or farmers who actually tilled the soil. College libraries contained the classics in literature, language, history, and basic sciences, but information related to production agriculture was limited. Agricultural research results were needed to build college courses. Results could be provided to farmers for improving their productivity and economic well being.

The Hatch Act, passed by Congress in 1887, provided the means of acquiring the needed research results and production information. Pioneering work in Europe, such as at Rothamsted in England, provided some of the guidelines to implement field studies. The pioneers of the national research program built upon the Hatch Act in order to learn more about the nature of the subjects they taught. These pioneers included Professors Manley Miles and George Morrow at the University of Illinois, J.W. Sanborn at the University of Missouri, A.C. Magruder at Oklahoma A&M College (now Oklahoma State University), and J.F. Duggar at The Agricultural and Mechanical College of Alabama (now Auburn University). From these early investigations, we now have the four oldest, continuous, field crop experiments in North America: Illinois' Morrow Plots (c. 1876), Missouri's Sanborn Field (c. 1888), Oklahoma's Magruder Plots (c. 1892) and Alabama's Old Rotation (c. 1896).

These early investigations were designed to answer a fundamental question, "What are the effects of manuring and crop rotations on sustainable crop yield?" Sanborn's question seemed to be, "Is it possible to sustain the production achieved when the prairie is converted to cropland?" Interestingly, these same

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questions reappeared in 1989 in the low-input, sustainable agriculture (LISA) movement which has captured national attention (5).

As the 20th Century arrived, the increased availability of commercial fertilizers such as blood meal, bone meal, kainit, guano, rock phosphate, and super phosphate, increased interest in soil fertility variables. Thus, commercial fertilizers were incorporated into some of the existing experiments and into most of the new agronomic research. The Morrow Plots, Sanborn Field, and the Old Rotation have demonstrated that crop rotations and manuring along with the use of commercial fertilizers can sustain production of corn and wheat in the Midwest and cotton in the South.

Under many conditions, fertilizers increased yields, especially of continuous crops. The profitability of fertilizer use caused a shift toward more intensive cropping both on farms and on long-term sites. Nitrogen fixed by legumes in crop rotations benefited grain and cotton production. However, the economic situation created by cheap N from 1955 through 1972 and the shift in types of farming from general to specialized tended to make rotations with legumes passé in most parts of the USA. Because these agronomic investigations have been continued, researchers are now able to study the effect of long-term fertilization and cropping systems on soil chemical and physical properties and sustainable crop production.

The purpose of this review is to form a list of the known, long-term agronomic, field investigations and to review the contributions these investigations have made on crop production.

LONG-TERM EXPERIMENTS IN NORTH AMERICA

The first challenge in compiling a list of North America's long-term agronomic research plots is to arrive at a definition or criteria for selecting experiments to be defined as long-term. Most of those that are presently considered long-term were not designed to be that way. Early research plots continued to yield valuable information or existing plots were modified to meet revised objectives. Rarely were they intentionally designed to meet objectives with a time limit. The 12 studies listed in Table 1 are those that have been in continuous production with soil amendment or cropping variables for more than 50 yr. They were identified through personal contacts with project leaders and administrators at agricultural research institutions in the United States and Canada. Three additional studies, a long-term wheat (c. 1893) and a long-term flax (c. 1895) study in North Dakota and a disease garden in Minnesota (c. 1913), were not included in Table 1 because they are maintained for disease study with no specific treatment variables. Alabama has the same study at six different locations but is listed only once (2).

None of the 19th century tests contained replicated treatments. The oldest study with replicated treatments is Alabama's "Cullars Rotation" (c. 1911) where the soil fertility variables were arranged in three blocks. However, treatments were not randomized within blocks (9).

Many of the more recent, long-term agronomic research experiments started in the 1950's were designed to study long-term effects of crop fertilization on yields and soil fertility (Table 2). All of these experiments involve large numbers of treatments using recognized experimental design such as randomized blocks, split plots or split-split plots, and factorial designs which allow more meaningful statistical analyses of soil and plant data. The long-term studies listed in Table 2 were selected because the project leader(s) consider them long-term studies; all have been monitored continuously for at least 25 yr.

Four of North America's oldest, continuous, agronomic studies, Illinois' Morrow Plots, Missouri's Sanborn Field, Oklahoma's Magruder Plots, and Alabama's Old Rotation, are listed in the United States National Register of Historical Places (1). The objectives and significance of these four long-term studies will be summarized in this paper.

THE MORROW PLOTS (c. 1876)

The Morrow Plots on the University of Illinois Urbana/Champaign campus are "... the oldest agronomic research plots in the United States and include the oldest continuous corn plot in the world" (11). These plots were also the first soil experiment established by a college in the United States. Like several of the existing long-term studies begun in the late 19th century, practical applied crop rotation investigations were the primary thrust of the study. Plots were large, 0.20 ha (0.5 acre), and treatments were not replicated. Through the years, some plots have been lost to development and the remaining ones reduced in size and subdivided three times. Parts of three of the original

Table 1. Active, long-term (50+ yr) agronomic studies in North America in chronological order of establishment.

Year of establishment	Location	Name of study	Primary crop(s)	Treatments/ variables	Replications	Nature of study
				no.	no.	
1876	Univ. of Illinois-Urbana	Morrow Plots	corn	18	None	rotation, fertility
1888	Univ. Missouri-Columbia	Sanborn Field	corn	44	None	rotation, manure, fertility
1892	Oklahoma State Univ., Stillwater	Magruder Plots	wheat	6	None	soil fertility
1896	Auburn Univ., Alabama	Old Rotation	cotton	13	None	rotation, nitrogen
1911	Auburn Univ., Alabama	Cullars Rotation	cotton, corn, soybeans, grain	14	3	soil fertility
1912	Univ. of Nebraska, Scotts Bluff	Continuous	corn	6	2	manure, nitrogen
1914	Univ. Missouri-Columbia	Duley-Miller Erosion Plots	corn, wheat, sod	5	None	soil erosion
1929	Auburn Univ., Alabama (6 locations in Alabama)	Two-Year Rotation	variable	17	4	soil fertility
1930	Univ. Alberta, Edmonton, Canada	Breton Plots	wheat, oats, barley forages	55	None	rotation, fertility
1931	USDA-ARS Pendleton, OR	Crop Residue	wheat	9	2	residue management
1932	Auburn Univ., Prattville, AL	Rates of Fertilizing Cotton	cotton	12	None	N, P, & K rates
1940	USDA-ARS Pendleton, OR	Tillage-fertility	wheat	3 main/6 sub	3	tillage and N fertilization

Table 2. Active, long-term agronomic studies since 1940.

Year of establishment	Location	Name of study	Primary crop(s)	Treatments/ variables	Replications	Nature of study
				no.	no.	
1941	USDA-ARS Kingdom City, MO	McCredie Erosion Station	corn, soybean	7	4	soil erosion
1951	Cornell Univ., Ithaca, NY	Lime I	corn, alfalfa, trefoil	11	8/16	Lime and cropping systems
1952	Purdue Univ., Indiana	Fertility vs. Crop Rotation	corn, soybean, wheat	22	2	fertility, rotation
1954	Auburn Univ., Alabama (7 locations)	Rates of N, P, K	variable	16	4	soil fertility
1954	North Dakota St. Univ., Fargo	Long-term Bromegrass	Bromegrass	6	2	N fertility
1955	Louisiana St., Bossier City	Winter Cover Crops on Cotton	cotton	8	4	N and legumes
1955	North Carolina St. (Tidewater Area)	Long-term P Study	corn, soybean	4×5	3	residual soil P
1959	Univ. of Minnesota, Lamberton	Rates and Sources of N Application	corn	4×3×2	4	N fertility
1961	Kansas State Univ., Tribune, KS	N-P-K Fertility	corn, sorghum	18	5	fertility
1962	Univ. of Wisconsin Arlington	Fertility	variable	4×4×4	2	rates of N, P, K
1962	Univ. of Wisconsin Arlington	Organic Amendment	variable	5	3	organic soil amendments
1962	Univ. of Wisconsin Arlington	pH	variable	5	3	soil pH
1963	USDA-ARS, Pendleton, OR	Wheat-Pea Fertility	wheat, green pea	4	4	tillage

10 plots remain with 18 subplots. Continuous corn (*Zea mays* L.), corn-oat (*Avena sativa* L.), and corn-oat-clover/alfalfa (*Melilotus alba* Medik. or *Trifolium pratense* L./*Medicago sativa* L.) were the primary rotations. The basic cropping patterns have been used throughout the history of the test with corn-soybean (*Glycine max* L. Merr.) replacing the corn-oat rotation in 1967.

Soil fertility variables have been added by dividing and subdividing the rotation plots. Lime, barnyard manure, rock phosphate and steamed bone meal variables were added later. Today, fertility variables include lime, urea applied to corn, barnyard manure applied at an amount equal to the amount of dry matter removed in the crop, two levels of soil test P maintained with triple superphosphate, residual soil P from previous applications of rock phosphate and steamed bone meal or manure, and no soil treatment. The uniformity of the site, the well documented records, and extensive soil analyses associated with the Morrow Plots justify maintaining them as a national treasure of information on long-term, sustainable crop production on a Midwestern United States soil (Flanagan silt loam, fine, montmorillonitic, mesic Aquic Argiudoll).

The Morrow Plots were established to settle a controversy about whether or not the prairie soils of the area could be depleted—another way of questioning sustainable agriculture. By 1904, plots of continuous corn were yielding 2.2 Mg grain ha^{-1} or 78% of the plots in a legume-based rotation. Conclusions were that (i) soils can be exploited and depleted and (ii) soils can be cropped and preserved.

By 1955, questions regarding the ability of fertilizers to restore or maintain productivity arose. Does exploitive cropping of unfertilized subplots cause permanent or temporary soil productivity losses? Will chemical fertilizers restore low-yielding plots to the production levels of the highest-yielding plots? If so, can this be done immediately or over a long period of time? The Morrow Plots showed that low yields caused by continuous cropping of non-eroded soils were due to loss of plant nutrients and not to irreversible changes. Fertilization restored productivity immediately and dramatically, but did not completely offset the effects of crop rotations. Crop rotations plus appropriate fertilization not only produced the highest crop yields, but also maintained soil N and organic C at the highest levels among the subplots.

Additional long-term observations from the Morrow Plots include:

1. For each cropping system, grain crop yields have continued a significant, straight-line or curvilinear trend upward during the various periods of uniform management. Improved varieties, especially hybrid corn, have contributed to the upward trend.
2. Yields of continuous corn were lowest and corn-oat-clover rotations were consistently highest whether the soil was fertilized with manure, lime, and phosphate or not treated.
3. Manure applications with lime and residual P produced lower long-term corn grain yields (6.3 Mg ha^{-1}) than treatments fertilized adequately with N, P, and K fertilizers (9.4 Mg ha^{-1}). Over 13.4 Mg ha^{-1} of corn was produced in 1982 on plots with a crop rotation and high levels of N, P, and K fertilization. This demonstrated the importance of sufficient fertilization with all primary nutrients for high, sustainable yields.
4. Application of lime, N, P, and K fertilizers on previously untreated soils dramatically increased corn yields nearly as high as the yields of subplots that had continually received manure, lime, and phosphate. This has also been demonstrated on long-term tests at six Alabama locations (2). Data such as these demonstrate that high and sustainable yields by many soils are limited only by easily corrected factors such as soil acidity and low levels of specific nutrients.
5. Larger yield differences were caused by soil treatments than by cropping systems.
6. Soil organic matter was higher under a corn-oat-clover rotation than under other cropping systems. Where lime, N, P, and K were applied beginning in 1955 to a previously untreated subplot, soil organic matter increased significantly. Soil N content followed the same pattern as organic matter (11).

As stated on the National Historical Marker adjacent to the plots, "... (The Morrow Plots) continue to provide data of the effects of crop rotations and the impact of organic and chemical nutrients on plant yields." (10).

THE SANBORN FIELD (c. 1888)

Sanborn Field at the University of Missouri-Columbia contains the second oldest, continuous research plots in North America and "... the oldest completely organized soil and crop experimental field in the U.S." (10). The field was "... designed to show the value of various rotations," but has also included tillage and soil fertility variables using manure. Upchurch et al. (12) stated that since the 1940s, "... justification has been based on historical dimensions of the field relative to developed and developing soil conditions under the different systems of management over extended periods of time." In 1979, objectives were clarified in response to threats to abolish the field and to help assure the integrity of the field and the continuity of cropping systems and soil treatments. Basic objectives for Sanborn Field are to: (i) determine long-term effects of soil treatments and crop management on the chemical, physical and biological soil properties; (ii) maintain a field laboratory where students and visitors can observe various crop management systems; and (iii) accumulate data on the effects of changes in soil properties upon crop yield components and composition of growing plants.

Sanborn Field, as well as the other 19th century research plots, emphasized what are now termed low-input, sustainable cropping and fertilization systems. Nine cropping practices or rotations and 4 soil treatments (no treatment, 2 rates of barnyard manure, and fertilizer N, P, and K) were included in the original 39 plots on a Mexico silt loam (fine, montmorillonitic, mesic Udollic Ochraqualf). These practices have been maintained but with some cropping and soil amendment changes on some plots. Cropping sequences were replicated but soil treatments were not. The field presently includes 13 different cropping practices and 20 variations in soil treatment on 44 plots. Crops produced in the various systems include winter wheat (*Triticum aestivum* L.), corn, alfalfa, timothy (*Phleum pratense* L.), red clover, bromegrass (*Bromus inermis* Leyss.), lespedeza (*Lespedeza* sp.), and soybean.

Sanborn Field has been used to demonstrate proven crop management practices, as a resource for other research, and to document the long-term effects of cropping systems and soil amendments on the soil ecosystem.

The long-term relationship of cropping system, soil organic matter, and N fertility has been extensively studied in Sanborn Field plots. An early objective of the experiment was to determine if rotations could increase soil organic matter and N and thereby increase yields. Initially, rotations did increase yields, but productivity soon declined unless nutrients removed in the harvested crop were replaced. In 1921, Miller and Duley (7) concluded that rotation alone could not put plant nutrients other than N back into the soil, and even N had decreased in soil from all plots. This led to the understanding that N loss from cultivation was a major reason cultivated soils lost productivity. Hans Jenny (6) reported a loss in soil N of 35% from a virgin prairie soil over a period of 60 yr of cultivation. His studies at the Sanborn Field also led to the conclusion that this decline does not continue indefinitely, but tends to reach a minimum level where it is again stabilized based upon cropping system and soil management (12).

Many of the observations and discoveries that document the history of the Sanborn Field have become established agronomic principles. These principles led to many recommended practices that modern growers have used for decades. Following are other practical, agronomic findings from the Sanborn Field:

1. Continuous legumes, legume systems, or animal manures will not maintain soil productivity without supplemental additions of plant nutrients. Organic material added to the soil must be supplemented and balanced with nutrient elements not present in residues and manures.
2. Continuous wheat does not remain productive over time whether manure or commercial fertilizers are used; weed and disease infestations cannot be controlled.
3. Crop rotations alone will not prevent deterioration of soil productivity.
4. Lime has been essential for legume establishment and growth and for subsequent N fixation.
5. Soil humus and P not only furnish nutrients to a growing crop but also buffer the effects of toxic elements such as Al.
6. Good yields can be produced only where proper amounts of essential elements are available at critical stages of plant growth.
7. Vigorously growing crops provide soil protection from erosion.
8. Cropping systems with sod or legume crops and/or soil treatments with barnyard manure or N are necessary to sustain soil humus.
9. Added nutrients also are of limited value in restoring soil productivity where soil erosion has removed topsoil and the remaining soil is of lower available water-holding capacity than the original topsoil.
10. Soil changes under known treatments have made possible the development of soil testing procedures now in use in Missouri and other states.

Sanborn Field history also demonstrates the value of long-term research plots to the non-agronomic scientific community. The field has become famous for the 1945 discovery of the bacterium *Streptomyces aureofaciens* Duggar 1948 strain A377 in soil from a continuous timothy plot without soil treatments. This was the ancestral parent of all the improved strains that produce the antibiotic aureomycin. The original soil sample from which the bacterium was isolated is now on display in the Smithsonian Institution in Washington, DC.

THE MAGRUDER PLOTS (c. 1892)

The Magruder Plots at Oklahoma State University in Stillwater, Oklahoma were established "... to obtain information about the ability of the prairie soil to produce continuous good wheat yields without fertilization" (13). Later, the site was divided and subdivided to include soil fertility variables from animal manures, rock phosphate, superphosphate, sodium nitrate, and muriate of potash. By 1930, 10 plots existed with manure and fertility variables.

Campus growth threatened the old plots until 1947 when surface and subsurface soil to a depth of 41 cm was physically removed from six of the treatments and relocated to another site. The original soil was a Kirkland silt loam (fine, mixed, thermic Udertic Paleustolls); the reconstructed plots are now 30.5 m by 5.3 m. The 6 treatments continued are:

1. Manure (applied every 4 yr at rate equivalent to 67 kg N ha^{-1} yr^{-1}).
2. No treatment since 1892.
3. P (14 kg P ha^{-1} yr^{-1} as superphosphate).
4. N and P (same as 3 above, plus 67 kg N ha^{-1} yr^{-1} as ammonium nitrate).
5. N, P, and K (same as 4 above, plus 27 kg K ha^{-1} yr^{-1} as muriate of potash).
6. N, P, K, and lime (same as 5 above, plus lime if pH < 5.6).

The following facts and principles of soil fertility management of Oklahoma prairie soils were learned from the Magruder Plots (13):

1. For 65 yr, P applications increased wheat yields but no yield increases were obtained from N, K, and lime.
2. After 65 yr, both N and P fertilization have been required for maximum yield.
3. Commercial fertilizer applications have improved yields as much as application of animal manures.
4. Potassium fertilization has had no noticeable affect on crop yields and liming has been only slightly beneficial.
5. Soil organic matter declined rapidly during the first 35 yr, maintained a lower rate of decline during the next 52 yr, and then stabilized.

THE OLD ROTATION (c. 1896)

The Old Rotation plots at Auburn University, Alabama are the oldest, continuous cotton (*Gossypium hirsutum* L.) research plots in the United States. This experiment was designed to demonstrate with cotton production in the Southern United States some of the same practices that the Morrow Plots and the Sanborn Field demonstrated with corn production in the Midwestern United States, i.e, the effect of crop rotations and legumes on sustainable crop production. The Old Rotation is located on a Pacolet sandy loam (clayey, kaolinitic, thermic, Typic Hapludults). This and similar acid, eroded, infertile, Coastal Plain and Piedmont soils supported an extensive area of cotton production during the late 19th and early 20th centuries. Continuous cotton with few soil amendments resulted in decreasing yields and profits for the growers. The Old Rotation attempted to demonstrate the effect of crop rotations and N-restoring winter legumes on a cotton and corn based production system.

Soil fertility variables were later added to study how P and K fertilization could be most efficiently incorporated into the various rotations. Today, the 13 large plots (41.5 by 6.5 m) include: (i) continuous cotton, (ii) a 2-yr cotton-corn rotation, and (iii) a 3-yr cotton-winter legume-corn-rye-soybean rotation. Crimson clover (*Trifolium incarnatum* L.) and vetch (*Vicia sativa* L.) and fertilizer N are used in several combinations to provide N for the cotton and corn. The P and K are uniformly applied to each treatment at the same rate in either split applications or to one of the crops in the rotation. The Old Rotation has been modified four times since it began, but some treatments are the same as in 1896. The last revision was in 1960 (3,4,8).

Following are some of the long-term observations from the Old Rotation:

1. Cotton yields have increased linearly since the 1920's in all plots except where cotton is continually produced without benefit of legume or fertilizer N.
2. Winter legumes sustained long-term, continuous cotton yields (10-yr mean of 0.68 Mg lint ha^{-1}) almost as high as yields produced with 134 kg N ha^{-1} yr^{-1} (10-yr mean of 0.70 Mg lint ha^{-1}).
3. A 3-yr rotation without direct N fertilization produced slightly higher cotton yield (10-yr mean of 0.83 Mg lint ha^{-1}) as a 2-yr rotation with N fertilization (10-yr mean of 0.70 Mg lint ha^{-1}). Corn grain yields were also higher with the 3-yr rotation (3.80 versus 3.27 Mg grain ha^{-1}).
4. Soil organic C in 1988 in the plow layer ranged from 0.12% in the continuous cotton plots with no legume and no fertilizer N to 0.33% in plots in the 3-yr rotation. Cropping system and winter legumes had a large influence on soil organic matter.
5. The timing of fertilizer P and K application had no effect on cotton yield or legume growth once soil test values reached and were maintained near a high rating for available P and K. Early data suggested that the winter legume (vetch) produced more growth that resulted in better cotton yields when P was applied to the legume rather than to the cotton (3,8).

CONCLUSIONS

America's oldest, continuous, long-term, agronomic research plots reflect the needs and resources available to the agricultural community of the late 19th Century. Land and labor were plentiful and agricultural statistics did not exist. Therefore plots were large and unreplicated. Soil amendments were limited to animal and unprocessed mineral ores in limited quantities. Crop rotations and N-restoring legumes appeared to offer growers the best opportunity to improve and sustain production. These early experiments have been changed to reflect the soil amendments and cropping systems of the times. They are the proven record of long-term, sustainable production.

Observations of changes in crop growth patterns or changes in soil properties with time in these long-term plots have led to additional investigations. These studies have resulted in many of the accepted principles of crop and soil management that are widely used today.

Because of the applied nature of these long-term tests, results have rarely been published in scientific journals that receive national and international exposure. Most records are limited to state agricultural experiment station bulletins and circulars. Refereed scientific journal articles from long-term, agronomic research are usually unrelated or remotely related papers involving specific soil or biological studies from selected treatments in the long-term study. However, without the records, soil, plant material, or isolated microorganisms from these sites, these more basic investigations might not have been possible.

The Morrow Plots, Sanborn Field, Magruder Plots, Old Rotation and several other long-term agronomic studies represent a unique agricultural resource from a historical, scientific, and social aspect. They have provided information on sustainable, profitable, agriculture from the 19th through the 20th Century, and, with adequate support and proper management, can lead sustainable agricultural research in North America into the 21st Century.

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