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Identification of Factors that Aid Carbon Sequestration in Illinois Agricultural Systems

by
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FINAL REPORT

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Executive Summary

Soil organic carbon (SOC) sequestration is important to climate change and cropland agriculture. Crops naturally use the greenhouse gas, carbon dioxide (CO_2), from the atmosphere; the greater the crop productivity the greater the amount of CO_2 used. Agronomic practices that enhance sequestration of crop biomass in soil as SOC also enhance removal of CO_2 from the atmosphere, and improve and sustain soil fertility. To effectively reduce the concentration of CO_2 in the atmosphere and mitigate climate change, sequestration of SOC must be long term, defined as decades or longer. This report presents a review and synthesis of scientific understanding of SOC sequestration, based on the history and genesis of soils and vegetation in Illinois, and the response of SOC and crops to agronomic practices. Recommendations for future cropland SOC research are made.

In order to improve the quantity and permanence of SOC sequestration, it is necessary to understand the soil-forming factors responsible for SOC sequestration in Illinois. Five interactive soil-forming factors are widely recognized (biology, parent material, climate, topography, time); however, the literature shows that human activity can be considered a sixth soil-forming factor. Human activities affect the soil-forming factors which govern SOC sequestration. Native American land-use practices of whole ecosystem manipulation were important in governing soil formation and SOC contents in Illinois, as were the land-use practices of the settlers who displaced them.

Most of Illinois is covered by geologic parent materials produced by the last Ice Age and the typical (modal) Corn Belt cropland soils of Illinois were formed from such geologic parent materials covered by tall-grass vegetation that was frequently burned by Native Americans and lightning. The frequent burning maintained tall-grass prairie over most of Illinois. Numerous soil analyses conducted during the early 20th Century showed that modal Corn Belt soils developed under Illinois' tallgrass prairies had two to three times the SOC of their forest soil counterparts in the top 1 meter (m). Fire frequency largely governed the distribution of forests and prairies. Forests covered only about one-third of pre-settlement (before ~1750) Illinois and were located mostly in landscape elements whose topography hampered fires. Therefore, the pre-settlement distribution of forest and prairie was determined largely by three soil-forming factors: topography, climate, and Native Americans.

Research conducted on humid, temperate natural areas (prairies and forests) of 20th Century North America indicate why such a great SOC difference in prairie and forest soils developed. Whereas both ecosystems produce comparable amounts of biomass, most forest biomass is aboveground and most prairie biomass is belowground where it is more efficiently incorporated into SOC. Furthermore, prairie biomass has higher concentrations of nitrogen (N) and other nutrients necessary to convert decaying biomass into humus — soil organic matter (SOM). Given the location of prairie biomass and its nutrient content, more prairie biomass becomes humus and therefore, a lesser proportion is lost to the atmosphere as CO_2 gas relative to forest biomass.

Research indicates that presettlement forests and prairies of Illinois had greater biological productivity, turnover, and SOC content than their natural area counterparts of the 20th Century. Fire regularly burned presettlement prairies and enhanced overall prairie productivity,

aboveground animal life, belowground microbial and animal activity, growth of legumes, and wetness. Fire produced charcoal — black porous carbon — which robust presettlement prairie microfauna and macrofauna incorporated more than 1 m into the soil. All of these factors coalesced to enhance SOC sequestration and SOC contents to levels greater than the 20th Century prairies, which have neither the fire frequency, legume richness, nor aboveground and belowground animal ecologies of presettlement prairies. Presettlement forests had a higher fire frequency that made for more fire-resistant tree species, a lower density of trees, and maintenance of a rich groundcover of herbs, legumes, and grasses that supported abundant wildlife. Most presettlement forests in northern, central, and southern Illinois were described as open and park-like, with a grassy, herbaceous, legume-rich groundcover of prairie plant species. Such forests would have developed more SOC-rich soils than 20th Century Illinois forests.

Changes in natural area forest and prairie SOC are believed to be much slower than those induced by plowing and other cropland agronomic practices. However, literature shows that rapid and large changes occur in prairies and forests with decreased fire frequency and animal activity. Such ecological changes result in SOC changes equal to or exceeding those reported for agronomic practices. For example, increased fire frequency increased SOC by 50 percent in the top 15 centimeters (cm) of a forest floor in about a decade by stimulating the growth of grasses and legumes. Conversely, protection of prairie from fire and grazing resulted in woody plant invasion and a 40 percent SOC decrease in the top 3 m in just 40 years. Additionally, after a century under forest, a prairie soil profile was converted morphologically into a forest soil profile.

This analysis of the history and genesis of soils and vegetation in Illinois shows that human manipulation of soil-forming factors can have a tremendous impact on SOC sequestration. Native American land-use practices influenced SOC. A more accurate estimate of the natural area SOC sequestration potential can be achieved by including the effect of the removal of Native Americans and cessation of their land-use practices. Current SOC sequestration potential estimates have excluded this important factor. Traditional agronomic cropland practices also influence SOC by manipulating soil-forming factors through plowing, draining, crop harvest, and erosion in ways that accelerate soil SOC losses. On average, 40 percent of plow layer SOC has been lost from cultivated prairie and forest Corn Belt soils compared to the SOC found in equivalent natural area soils. However, whole-soil SOC change — SOC changes in the top 2+ m of soil — has yet to be quantified. This is an important task, especially for prairie-derived Corn Belt soils, because in the top 1.5 m of soil, over 80 percent of SOC lies below the plow layer.

Time was assessed as a soil-forming factor for SOC contents of soil-development sequences, also called soil-maturity sequences. Chronological age is not an adequate definition of time because the “effective age” of a soil is also influenced by the other soil-forming factors. As soils develop, the most easily weatherable minerals are released; a portion is lost from the soil, a portion is taken up by plants, and a portion is stored in plant-available form in SOM. As soils continue to develop, their banks of SOM and plant-available nutrients grow to maturity, i.e., achieve their maxima. As soils age past their peak productive years, they become more acidic. With increased acidity and decreased P and K, N fixation and biological productivity decrease. Because formation and maintenance of soil humus requires N, P, sulfur (S), and other nutrients, all of the above factors conspire to reduce SOC sequestration in post-mature soils as effective age increases. In such aging soils, fine-soil aggregates produced by plant and animal pedoturbation decrease, with loss of aggregation becoming more pronounced with soil depth. As a result, soil structure becomes more massive, and SOM becomes less exposed to (more protected from) decomposition by already diminished weathering capacity of biological activity. The age of bulk-soil SOC increases as turnover rates decline; however, old SOC quickly decomposes locally around roots by the high biological activity of the rhizosphere, and SOC turnover is greater than that inferred from bulk-SOC age.

Aged soils can be rejuvenated — acidity neutralized, and nutrients restored — naturally and/or by anthropogenic activities. With rejuvenation, root systems become larger and older SOC is available to the high biological activity of the rhizosphere. The discrepancy between actual SOC turnover rate and SOC turnover rate inferred from bulk-SOC age becomes even larger with rejuvenation.

In recent decades, herbicides and pesticides have enabled the widespread practice of low- and no-till agriculture, and other reduced tillage practices. With the shift to these shallow tillage practices, research emphasis shifted to evaluating SOC changes in shallow soil depths (2.5 to 30 cm). With this shift in research emphasis has come a shift in the reported effects of agronomic practices on SOC and soil fertility: reduced tillage practices are reported as having reversed the trend from SOC and nutrient loss to modest SOC and nutrient gain. However, crops influence SOC and soil nutrient status throughout their depth of rooting which, for corn, averages 1.8 m in Illinois. Thus, research that studies the effects of agronomic practices on the entire root zone of cropland soils is needed. Such research has implications for SOC sequestration and other contemporary issues such as water quality, soil fertility, and sustainable agriculture. Research on the effects of agronomic practices has quantified chemical and physical processes in the surficial soil layers, but there has been little quantifying of these processes in the deeper soil layers. Nevertheless, it is in these deeper soil layers where potential long-term SOC and nutrient depletion and sequestration are greatest. And, since water also drains through these deeper soil layers, research based on a whole-plant/whole-soil perspective is needed to better determine the effects of agronomic practices on water quality.

This report made an important discovery; namely, whole-plant/whole-soil research need not start from scratch. Early agronomic research conducted in Illinois and elsewhere during the 19th Century and the first half of the 20th Century recognized the importance of SOC to soil fertility and successfully experimented with whole-soil SOC sequestration. Studies have shown that conventional cropping practices of the past have, in some cases, increased whole-soil SOC content to values greater than their 20th Century natural areas counterparts, particularly for forested soils. Research showed that building SOC necessitated building nutrients in soil to convert biomass to soil humus. Human activities can act as a geologic agent in the soil-forming process to arrest soil aging and rejuvenate aged soils by adding plant-available nutrients above and beyond plant requirements. Crop biomass input can be maximized throughout the soil by stimulating deep and robust root growth, and surface-applied fertilizer nutrients can be mobilized throughout the root zone to maximize biomass conversion and stabilize organic carbon in soil humus. Research in Illinois 50 to 100 years ago demonstrated ways to increase whole-soil SOC in naturally-low-SOC soils, as well as in relatively-high-SOC prairie-derived cropland soils which is a much more difficult task.

With the shift of agronomic research to heightened concerns about water quality and other environmental issues, agronomic research searched for ways to minimize nutrient inputs and mobilization of nutrients needed to sequester SOC in the root zone. Fertilizers came to be deposited on the surface or shallowly incorporated, and the chemistry of the applied fertilizers changed so that lime and fertilizer nutrients were no longer mobilized to move deep into the soil. Aboveground plant residues came to be left on the surface or partially and shallowly incorporated in order to reduce erosion and runoff. An important consequence of this shift in agronomic research perspective was the development and application of agronomic practices that tend to promote shallow rooting in the concentrated fertilizer zone of the SOC-enriched surface layer, whereas the practices of the early 20th century tended to promote deep and luxuriant root growth. Shallow rooting makes crops more susceptible to periods of deficient moisture. Eventually, subsoil impoverishment and fertilizer concentration at the surface will decrease plant productivity, biomass incorporation into the soil, and efficiency of biomass conversion to soil humus.

An important finding of this work is that to reduce the atmospheric CO_2 content and sustain cropland agriculture, SOC must be sequestered throughout the soil profile. The modern literature reports SOC increases when tillage is changed from conventional to conservation tillage practices. However, SOC measurements are surficial, usually no more than the top 30 cm, with most of the C being sequestered in the top 15 cm. The unstated assumption in the modern literature is that surficial SOC changes represent all the SOC changes in the soil profile. This work shows that the SOC losses in the deeper soil layers may overwhelm surficial SOC increases. In order to assert that C is being sequestered in the soil, the whole-soil profile must be considered.

It is recommended that future research into SOC sequestration be conducted from a whole-plant/whole-soil perspective in a soil genesis context using the following strategies.

Mine the Literature. Most of the literature needed to provide the requisite whole-plant/whole-soil perspective and soil genesis context is scattered and not organized, summarized, or synthesized in the current SOC sequestration literature. The evolution of SOC sequestration research has been a narrowing of perspective away from the more holistic whole-plant/whole-soil perspective of the foundational agronomic literature to the near-surface soil layer. This vast scientific foundation needs to be located, restored, and incorporated, along with the current literature on crop rhizosphere and C and nutrient cycles throughout the whole-soil profile, soil genesis, soil fertility, subsoil amelioration, and other literatures, and organized, summarized, and synthesized into the SOC sequestration literature.

Long-term Whole Plant/Whole Soil Monitoring and Assessment. Assessment of the effects of agronomic practices on SOC must be expanded to include the whole-soil profile. Improved estimates of presettlement soil SOC contents are needed to better assess SOC loss and SOC sequestration potential of Illinois' prairie and forest soils. The magnitude and swiftness with which natural factors govern SOC contents need to be better identified and quantified while incorporating a more comprehensive definition of soil aging and both presettlement and postsettlement anthropogenic landscape management practices as soil-forming factors.

SOC Sequestration Research. Finally, research on how agronomic practices can increase SOC throughout the soil profile needs to be conducted from a whole-plant/whole-soil perspective in a soil genesis context. This report indicates that the optimal way to sequester SOC is to convert land back to native prairie, burn frequently, add fertilizers, and remove anthropogenic surface and subsurface drainage. Such an approach is not practical. Constraints on optimizing cropland SOC sequestration include: 1) the need to maintain good soil drainage in Illinois soils for timely spring planting that allows for growth of long-season corn hybrids and soybean varieties; and 2) maintaining soil-nutrient levels that do not result in water-quality issues.

Within these constraints, the authors hypothesize that SOC sequestration can best be done by 1) developing balanced soil-fertility programs and other agronomic practices that restore soil nutrients to levels optimum for plant growth, promote movement of plant nutrients throughout the root zone using organic and/or inorganic carriers, and promote deep rooting of plants with minimal mechanical disturbance of the soil by tillage; and 2) developing chemical pest control programs that minimize the effects of pesticides on soil bacteria, and microfauna and macrofauna, thus promoting conversion of biomass to SOC, pedoturbation and net movement of SOC through the soil profile, and creation of soil structure and aggregation that optimize biomass production and conversion to stabilized SOC. Research on the development of these practices must include evaluation of nutrient movement into ground and surface waters.

Losses of SOC have occurred on the order of the century time scale. SOC sequestration — and the measure of its success (permanence of SOC sequestration) — are also necessarily measured on the order of the century time scale. Therefore, long-term (20 to 30 year) agronomic SOC sequestration research at both the farm and individual plot level needs to be designed and conducted for hypothesis and model testing, as well as evaluation of the permanence of SOC in the surface and whole-soil profile. Even longer-term research needs to be designed and conducted for hypothesis refinement and for monitoring.

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Introduction

Soil organic carbon (SOC) sequestration is important to climate change and agriculture. Human activities are estimated to have enhanced the greenhouse effect largely by increasing the quantity of carbon dioxide-carbon (CO_2-C) in the atmosphere from 600 billion metric tons in pre-industrial times to more than 750 billion metric tons (e.g., Siegenthaler and Sarmiento, 1993). Estimates of terrestrial C release to the atmosphere since 1860 range from a net of 120 billion metric tons to 228 billion metric tons with about equal amounts estimated to be contributed from loss of soil C and biota C. Only part of the net loss of terrestrial C to the atmospheres remains there. The rest is redistributed to other C reservoirs such as the ocean and mineral weathering (Arrhenius, 1896; Houghton et al., 1983; Siegenthaler and Sarmiento, 1993; Konyushkov, 1996). Losses of soil C and nitrogen (N) are reported as being in direct proportion to each other (Albrecht, 1938; DeTurk, 1938; Jenny, 1941; Odell et al., 1984a; Stevenson, 1986). Assuming a C:N ratio of 10 to 12, estimated agricultural loss of soil C in the United States since the 1860s is ~20 billion metric tons (Viets and Hageman, 1971). Assuming that this loss occurred from the topsoil (top 30 centimeters (cm)) of ~160 million hectares (ha) of cropland, average loss was 123.5 metric tons C ha^{-1}.

Sequestration of CO_2 and long-term storage as SOC is being considered as a strategy to reduce atmospheric CO_2 concentrations in order to mitigate climate change. A successful strategy to sequester CO_2 as SOC in agricultural soils provides the opportunity for producers to participate in carbon trading. The potential for Illinois soils to sequester C is significant. Assuming that Illinois cropland soils are representative of the United States average, restoration of Illinois cropland soils to presettlement SOC status represents a 1.15-billion-metric-ton C sink for atmospheric CO_2-C, based on the above assumptions and current understanding. The potential of cropland soils to sequester CO_2-C is even larger than the estimated loss of cropland SOC. With proper fertilization, organic additions and cultural practices, the factors controlling soil formation can be modified such that agricultural soils theoretically can increase their SOC content to greater than the inferred preagricultural levels (Jenny, 1941; Johnson, 1995; Swift, 2001).

Sequestration of SOC is important to agriculture as SOC is the major constituent of soil organic matter (SOM), a time-release supply of plant nutrients that improves the soil's physical properties of water-holding capacity, aeration, internal drainage, and soil tilth. The introduction of European agriculture in the Midwest Corn Belt altered soil-forming factors so that an estimated 40 percent of SOC (Mann, 1985) and an estimated 40 percent of N (Stevenson, 1986, p. 55) were lost from the plow layer. Early studies in Illinois, Indiana, and Wisconsin for a variety of crops indicated a loss of about one-third of soil phosphorus (P) from the plow layer after about 50 years of cultivation (Hopkins, 1910). A century of mining the soil of its nutrients (e.g., N, P, potassium (K), sulfur (S), calcium (Ca), and magnesium (Mg)) caused natural soil fertility — and concomitantly SOM and crop yields — to decline to the point that nutrients had to be chemically added to croplands in order to feasibly continue agriculture (e.g., Conner, 1922; Albrecht, 1938; DeTurk, 1938; Whiteside and Smith, 1941; Viets and Hageman, 1971; Odell et al., 1984a; Stevenson, 1986).

To sequester SOC in agricultural systems and how much SOC may be potentially sequestered, the importance of soil-forming factors operating in Illinois must be understood. This was accomplished by reviewing the literature on the history and genesis of soils and vegetation in Illinois, the rapidity of prairie and forest soil conversion, and the response of SOC to agricultural practices from a soil genesis perspective. In the section on the history and genesis of soil and vegetation in Illinois the literature on the effects of fire and animals on the prairie and forest, and soil aging are reviewed. The section on rapidity of prairie and forest soil conversion examines the changes in soil after prairies have been replaced with forests and after forests have been replaced by prairies. The section on the response of SOC to agricultural practices looks first at the loss of SOC induced by agriculturally-related changes, and secondly agricultural management practices that encourage SOC sequestration.

The History and Genesis of Soils and Vegetation in Illinois

The history of science shows that understanding a system necessitates acquiring more data and knowledge than provided by research of just the system alone. Therefore the history and genesis of soils and vegetation in Illinois and the surrounding states were researched to provide the requisite big picture of how soil-forming factors govern SOC sequestration and depletion in Illinois.

While traditionally five interactive soil-forming factors are recognized, as noted by Jenny (1941, pp. 232-260), human activity can be so significant that it may be considered the sixth factor. This report defines six interactive soil-forming factors as having governed soil formation and SOC content in Illinois: biology, parent material, climate, topography, time, and Native Americans. A discussion of the effects European agricultural practices on soil formation is presented in the section on the response of SOC to agricultural practices.

Regarding the biological soil-forming factor, grasslands are the largest vegetation type of North America (Sims, 1988) and Illinois. The predominant presettlement (before 1750) landscape element of the “Prairie State” was grassland — mostly moist (tallgrass) prairie, also called “True Prairie” (Risser et al., 1981). In 1820, prior to extensive European settlement, land surveys showed that prairie covered ~9 million ha of Illinois' ~14.5 million ha of land (Iverson et al., 1989).

The True Prairie ecosystem is young, having come into existence only some 10,000 years ago during the present interglacial period, the Holocene. It was during this time that True Prairie replaced forest east of a north-south line that runs through the eastern Dakotas down through eastern Texas. Soil scientists call this line the “lime-line” and which is largely a function of the climatic soil-forming factor. West of the lime-line it is so dry that precipitation generally does not penetrate through the whole-soil profile. It is here that carbonic acid weathering of soil minerals results in the precipitation of carbonates (CO_3) in subsoils (Risser et al., 1981; Sims, 1988). Approaching the lime-line from the west:

“Eastward, under a gradually increasing precipitation, the carbonate layer becomes deeper. In the mixed prairie it occurs at levels varying from about 2 to 5 feet [0.6 to 1.5 m]. Below the carbonate layer dry soil is found. Where the precipitation averages approximately 30 inches [76 cm]...the subsoil is permanently moist and the carbonate layer has quite disappeared.... The depth of the carbonate layer delimits the area in which the absorption of water and nutrients [by plants] usually occurs” (Weaver, 1927, p. 5).

"The large soil volume thus afforded for absorption of water and nutrients undoubtedly accounts in a great measure for the luxuriant above-ground development. In the subclimax prairie eastward (of the lime-line), the water relations are even more favorable" (Weaver, 1927, p. 6). Plant and ecosystem productivity increases with increasing moisture (e.g., Weaver, 1927; Sala et al., 1988). This interaction of the biological and climatic soil-forming factors results in increasing SOM and SOC content (Figure 1) — soil N being used as a surrogate for SOM and SOC (Jenny, 1941).

East of the lime-line, the climate is so wet that soil water leaches completely through the soil profile and prevents the precipitation of carbonates. East of the lime-line a "Prairie Peninsula" — shaped like an arrow head pointed into the heart of the Ohio Valley — was formed out of forest during the very warm mid-Holocene Climatic Optimum (Ruhe, 1983; Kucera, 1992). The Prairie Peninsula is True Prairie, i.e., tallgrass prairie (Kucera, 1992). Most of Illinois became tallgrass prairie 6,000 to 7,000 years ago:

"There are few plants endemic to North American grasslands (these being primarily forbs). This is also true for insects, birds, and mammals which originally come from the bordering forests. The lack of endemism is attributed to the fact that these grasslands are unique, coming into existence only after the last ice age" (Sims, 1988, p. 267).

True Prairie never developed during any previous interglacial period, not even during the Sangamon Interglacial 120,000 to 130,000 years ago when the Arctic Ocean was typically ice-free and Arctic temperatures were above 0ºC (Daugherty, 1968), even hotter than during the mid-Holocene Climatic Optimum (Lamb, 1977, pp. 323-342; 1995, p. 358; Bradley, 1999; Teed, 2000; Muhs et al., 2002). Trees were more prevalent in Illinois during the Sangamon Interglacial than during the Holocene (McComb and Loomis, 1944; Teed, 2000). But the Prairie Peninsula persisted — and even expanded northward (e.g., Hole, 1976, pp. 53-56) — when the climate was becoming even more favorable for forest growth and less favorable for prairie as the region around Illinois started becoming cooler and wetter around 7,200 years ago (Knox, 1983; Grimm, 1984; Dean, 1997). At that time the warmth of the Holocene Climatic Optimum was being replaced by the present worldwide Holocene Neoglacial (Matthes, 1939; 1941; Porter and Denton, 1967; Denton and Porter, 1970; Davis, 1988; Matthews, 1991; Nesje et al., 1991).

The True Prairie is unique in natural history. This uniqueness correlates with another unique condition — the presence of *Homo sapiens*:

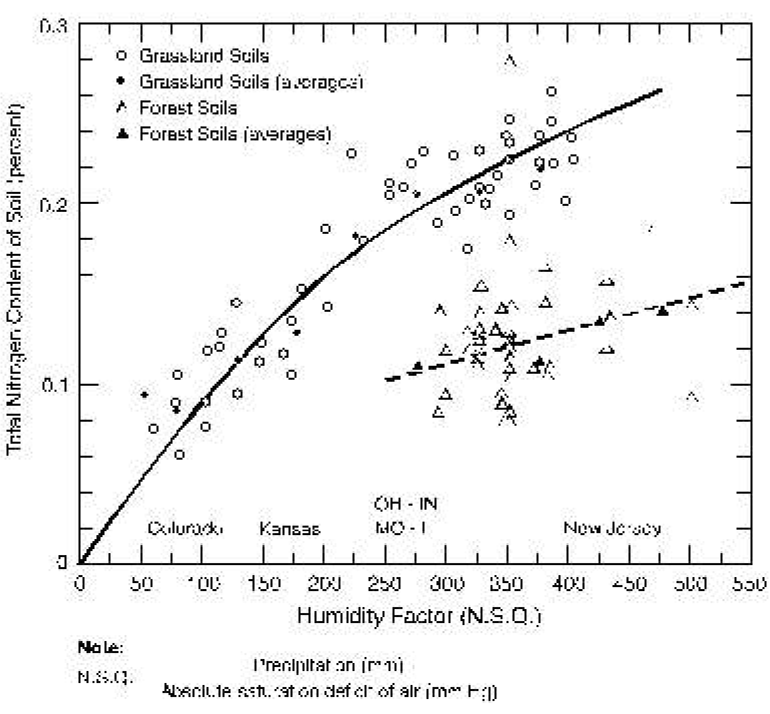

Figure 1. Soil nitrogen-humidity relationship for prairie and forest soils of the central and eastern United States along the annual 11˚C isotherm. Source: Jenny (1941).

“It is often suggested that, since the Indian was a principal agent in landscape fires, such fires were ‘unnatural,’ although the corollary is rarely expressed: the resulting prairies and oak groves are unnatural. Perhaps it can be suggested that withholding fire from biota accustomed to millennia of burning is no less natural. The Tall Grass Prairie biome evolved with the Indian, and Indian culture adapted itself to the biome” (Wilhelm, 1991, p. 44).

Fire and Prairie

Old World-based cultures view land through an Old World concept; namely, improved land is typically that land which has at some time been cleared or underlies human structures. Land improvement by the natives of the New World involved whole ecosystem manipulation to produce the “fruited plains.”

Fire, both natural and anthropogenic, was instrumental in maintaining the distribution and composition of both Illinois’ prairie and forest. Lightning, a climatic element, started fires. And Native Americans relied heavily on fire as a land-management tool:

“The prairie fire was part of the lore of the Midwest and is remembered as ‘Indian Summer,’ a dry time of late fall when the air was hazy with smoke. At that season Indians were accustomed to set fire to the sere vegetation...” (Sauer, 1975, p. 12).

The prairie reportedly burned almost annually, usually during the fall and spring of the dormant season (Gleason, 1913; Sauer, 1916; Shull, 1921; Malin, 1953; Curtis, 1959, pp. 295-305; Bakeless, 1961; Old, 1969; Bragg and Hulbert, 1976; Pyne, 1983; Grimm, 1984). The presence of prairie or forest largely was determined by fire frequency, with forest frequency being most prevalent in south and north hill countries and along riverbanks and sloughs whose topography helped protect against fire (Short, 1845; Gleason, 1913; Vestal, 1918; Jenny, 1941; Shrader, 1946; Iverson et al., 1989):

“It is true therefore, as a general rule, in relation to the states in which prairies are situated, that wherever there is a considerable tract of surface, not intersected by water courses, it is level, and destitute of timber: but in the vicinity of springs and streams the country is clothed in forest.

“Taking as an example the country lying between the Ohio and Mississippi rivers, it will be seen that in the point formed by their junction, the forest covers the whole ground, and that as these rivers diverge, the prairies begin to intervene. At first there is only an occasional meadow, small, and not very distinctly defined. Proceeding northward the timber is found to decrease, and the prairies to expand; yet the plains are still comparatively small, wholly unconnected with each other, and their outlines distinctly marked by the woodlands which surround and separate them. They are insulated and distinct tracts of meadow land, embosomed in the forest. Advancing further to the north, the prairie surface begins to predominate; the prairies now become large, and communicate with each other like a chain of lakes, by means of numerous avenues or vistas; still however, the traveler is surrounded by timber; his eye never loses sight of the deep green outline, throwing out its capes and headlands; though he sees no more of those dense forests and large trees, whose deep shade almost appalled him in the more southern district.

“Traveling onward in the same direction, the prairies continue to expand; until we find ourselves surrounded by one vast plain. In the country over which we have passed, the *forest* is interspersed with these interesting plains; *here* the *prairie* is studded with groves and copses, and the streams fringed with strips of woodland. The eye sometimes roves over an immense expanse clothed with grass, discovering no other object on which to rest, and finding no limit to its vision but the distant horizon; while more frequently it wanders from grove to grove, and from one point of woodland to another, charmed and refreshed by an endless variety of scenic beauty.

"This description applies chiefly to Illinois, from careful inspection of which state we have drawn the picture; but its general outlines are true of Indiana and Missouri, and are applicable, to some extent, to Ohio and Michigan" [Hall, 1837, pp. 77-78 (emphasis his)].

In central Illinois, a more detailed description of the relationship between fire, forest, and prairie distribution was given:

"In a previous paper (1912), referring to the location of certain isolated groves in central Illinois, it was shown that they were uniformly situated on the eastern side of prairie sloughs, and the conclusion was advanced that their existence in these places was due to the protection against prairie fires furnished by the water barrier. Since the publication of this paper, a number of similar facts have come to hand, all serving to indicate the efficiency of ponds and streams in protecting forests from the incursions and destructive effects of prairie fires. In general it may be said that the location of forests throughout central and northern Illinois, and also through the adjacent states, is closely correlated with prairie fires.

"It is well known that the prevailing winds throughout most of the Middle West come from the west, varying from northwest to southwest. Prairie fires would, therefore, in most cases travel toward the east, and would attack the forest on the west side..." (Gleason, 1913, p. 173).

"...it is doubtful if mature trees were ever killed by a single fire. But the seedlings must certainly have been destroyed in large numbers, and the repeated charring of the bark of the larger trees led after a few years to their death. Statements to this effect may be found in several of the older books of travel. Loomis (1890) states: '...the heat and fury of the flames driven by a westerly wind far into the timbered land...destroying the undergrowth of timber, and every year increasing the extent of prairie in that direction, has no doubt, for many centuries added to the quantity of open land found throughout this part of America.' Brackenridge (1814, p. 109) makes a similar statement..." (Gleason, 1913, p. 175).

Native American land-use practices enhanced SOC sequestration. Overall, Heal and Ineson (1984) report that mean net primary productivity is 13 metric tons ha^{-1} per year (yr^{-1}) in temperate forest and 15 metric tons ha^{-1} yr^{-1} in temperate grassland. Of this, the forest puts 20 percent (2.6 metric tons ha^{-1} yr^{-1}) below ground and grasslands 60 percent (9.0 metric tons ha^{-1} yr^{-1}). Temperate grassland soils have nearly double the SOM of temperate forest soils — 220 versus 120 metric tons ha^{-1} (Schlesinger, 1977; Heal and Ineson, 1984) — much of the difference due to deeper incorporation of greater amounts of SOM under temperate grasslands (Schlesinger, 1977).

Interactive biological, climatic, and Native American soil-forming factors superimposed themselves on the underlying geologic parent material and time. Modal soils of Illinois were formed under prairie vegetation from geologic parent materials produced from the last Ice Age — mostly loess — with a sizeable fraction also formed under forest (Hopkins, 1910; 1913, pp. 10-11; Jenny, 1941; Smith et al., 1950; Fehrenbacher et al., 1984). In Illinois, all else being equal, data collected during the early 20th Century show that modal soils developed under prairie vegetation tend to have about twice the C and N of their forest soil analogs in the top 25 cm (Jenny, 1941), and two to three times as much in the top 100 cm (Hopkins, 1910; Figure 2) as SOM is more deeply distributed in prairie than forest soils (Hopkins, 1910, pp. 82-87; Soil Conservation Service, 1968). Of the SOM that existed between the surface and 1.5 m depth in the prairie soils of the Corn Belt in the early 20th Century, slightly less than 20 percent was in the plow layer and slightly more than 80 percent was between the plow layer and 1.5 m soil depth. These analyses showed as much SOM in the 1 to 1.5 m layer as there was in the 0 to 15 cm layer.

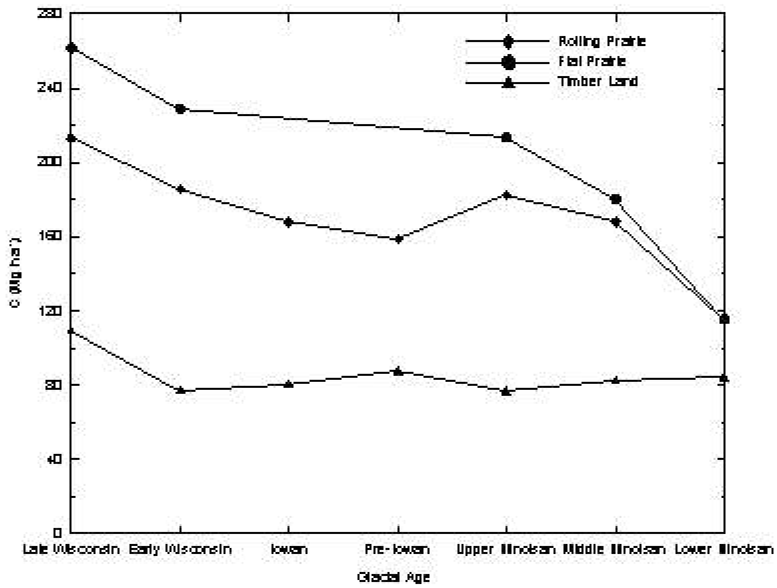

Figure 2. Effect of vegetation and time on soil organic carbon (SOC) in the top 1 meter (40 inches) of Illinois soils. **Source:** Data from Hopkins (1910).

Soils developed under forests have negligible SOM below 1 m (Hopkins, 1910, pp. 82-87; Marbut, 1929; Schreiner and Brown, 1938; Soil Conservation Service, 1968; Krug and Winstanley, 2002).

Fire, by favoring prairie vegetation over forest, further enhanced SOC sequestration by greatly narrowing the C:N ratio of the soil-forming plant litter as the C:N ratio of grass and legume biomass is far lower than that of forest biomass (Albrecht, 1938; Jenny, 1941; Stevenson, 1986, Table 5.3).

By maintaining land in prairie, fire also appears to have made Illinois' landscape wetter since prairie soils are wetter than their forested counterparts as trees transpire more:

"Hibbert...summarized 30 forest cutting and poisoning experiments in the United States, Africa, and Japan, as well as nine additional cases in which streamflow increases were studied for some years following afforestation. The controlled experiments all showed significant changes in water yield, averaging about eight inches [20 cm] increase following elimination of fully stocked stands and about the same decrease 20 or 30 years after afforestation. Although there is no space to discuss them here, dozens of soil moisture studies have verified the fact that forest removal or conversion to other vegetation types reduces evaporative draft on soil water and increases the opportunity for these 'savings' to be delivered as streamflow" (Hewlett, 1967, p. 155). And these wetter soils naturally accumulate more SOM (Hopkins, 1910; Krug and Winstanley, 2000).

The above five interactive soil-forming factors are superimposed upon topography. This increased wetness would have been expressed across the soil drainage catena, especially in the lower portions of the landscape as greater amounts of water would drain from higher to lower landscape elements. Whereas internal drainage is commonly believed to be responsible for the gradient of increasing SOC and nutrients across the catenary soil sequence of upland to lowland soils (e.g., Hopkins, 1910; Soil Survey Staff, 1962), lateral surface and subsurface drainage and erosion of dissolved and suspended materials from upland to lowland positions make drainage catenas geochemical catenas as well (Aandahl, 1948; Glazovskaya, 1970; Krug, 1981; Schimel et al., 1985).

The typical Illinois catenary drainage sequence is also one of increasing primary productivity and increasing organic additions — ever-increasing shoot and root production from upland prairie down through the zone of emergent freshwater vegetation, the latter is the most productive landscape element of all (Sampson, 1921; Weaver, 1926, 1954, 1958a; Evers, 1955; Hadley and Kieckhefer, 1963; Old, 1969; Sutton, 1976; Wetzel, 1979):

“ ‘The bottom Prairies are covered with Weeds of different kinds of grass about 8 feet high. The high Prairies are also thickly covered with grass but finer & not so tall.’ ” (Sutton, 1976, p. 141).

It has been found that the quantity of biomass in 0 to 60 cm of soil under prairie across the drainage catena increases downslope from 8 to 13 times that found under cropland drainage catena counterparts. The difference is even greater in the 60 to 180 cm layer: prairie root biomass is 10 to 22 times that found under cropland drainage catena counterparts (Slobodian et al., 2002).

The quantity of soil N in the top 1 m has been measured to range from about an average of 6,700 kg ha^{-1} in excessively drained upland soils to an average of 224,500 kg ha^{-1} in wetland Illinois soil (Hopkins, 1910, pp. 82-87). Soil-forming conditions found in Illinois transcend the state’s political boundaries. Soil scientists report Hopkins’ Illinois soils N data (Hopkins, 1910, pp. 82-87) as the average values of the major soils types common to the North Central States (e.g., Bear 1929, Table 10; Schreiner and Brown, 1938, Table 3) and as the average values for these soils types throughout the United States (e.g, Stevenson, 1982, Table 3; Stevenson and Cole, 1999, Table 5.4). The range in SOC is slightly greater as C:N ratios are somewhat larger in organic-rich wetland soils than in upland soils, and the depth and SOC content of wetland soils are greater (Hopkins, 1910; Stevenson, 1986).

Fire, by favoring prairie vegetation over forest, enhanced SOC sequestration by increasing the depth distribution of SOM. True Prairie plant ecology and animal ecology — belowground and aboveground — formed the deep, dark, and fertile soils of the Corn Belt. Aboveground plant ecology of the True Prairie was described by Allen (1870, p. 580):

“From the first springing up of the early flowers till the frosts of autumn end the floral season, the prairies are arrayed in bright and showy hues by a succession of species of larger and taller growth, each later set not only overtopping their predecessors, but the rapidly growing prairie grasses.”

“The original prairie consisted chiefly of big bluestem (*Andropogan furcatus*) with an admixture of a considerable number of other grasses, legumes, and various other forbs. The grasses commonly reached a height of 6 to 8 feet [1.8 to 2.4 m], and formed a very tough sod” (Smith et al., 1950, p. 168).

Whereas annual aboveground production of presettlement tallgrass prairie was evidently great, productivity was even higher belowground:

“Sixty to 90 % of the net primary productivity (NPP) and 90 % of the secondary productivity occur in the soil: the former as roots, the latter as microorganisms...a significant percentage of live roots in grasslands are consumed by herbivores in the soil.... Thus in the belowground system, there are at least two major trophic pathways: herbivory and decomposition. Each pathway is regulated by the primary resource, roots, and by hundreds of species of secondary consumers preying on members within each tropic pathway” (Stanton, 1988, p. 573).

True Prairie is dominated by deep-rooted species. Most tallgrass-prairie species send their roots to three different soil depths: shallow-rooted species $\leq$ 0.6 m, medium-rooted species 0.6 to 1.5 m, and deep-rooted species $\geq$ 1.5 m, with most species sending their roots $\geq$ 1.8 m. Legumes and some other plants drove their roots down > 5m (Weaver, 1954, 1958b; Lerner, 1980; Risser et al., 1981; Prairie Frontier, 2002). The timing of the development of aboveground parts of different species not only gives tallgrass prairies ever-changing seasonal aspects, it supports dense growth (often 200 to 250 plants per square meter (m^{-2})), and distributes the demand of the prairie on soil resources across the growing season. The predominance of deep-rooted species enables tallgrass prairie to use soil nutrients and water to the end of the growing season long after more surficial resources would otherwise have been used up:

"Relatively few of the deep-rooted species (only about one-fifth) rely to any marked degree upon the shallow soils for their water and solutes, while many carry on relatively little absorption in the first, second, or third foot. This root habitat is in marked contrast to that of the majority of plants of the mixed prairie, where surface rootlets are often extremely well developed. This appears to result from the true prairie's rather uniformly greater moisture in the deeper soil.... The true-prairie species as a community emphasize depth of penetration and wide spreading, deep laterals" (Weaver, 1954, p. 116).

This results in deep soils rich in SOC and associated nutrients — soils of exceptionally high-SOC content and subsoil fertility:

"The deeply rooted species have modified the soil to great depths, enriching it with nitrogen, adding humus by root decay, as well as by making it more porous. As a result of absorption, vast stores of nutrients have been brought from the deeper soils, and, upon the deaths of the tops, deposited in the surface soil. Thus, the prairie furnishes the most productive region for agriculture" (Weaver, 1954, p. 117).

Fire not only made possible the True Prairie, fire enhanced its growth by removing stifling amounts of plant litter that physically suffocated plant growth and seed germination. Plant litter also stifled plant growth by tying up needed nutrients (especially N) and by providing an unfavorable microclimate. Prairie litter also contained allelopathic substances that inhibited plant growth, and desirable forms of microbial activity (Old, 1969), e.g.:

"No other known system produces foliage like that of tallgrass that must contend with an accumulation of detritus two to three times greater than its annual production. Thus in areas where woody plants have not invaded (e.g., sites far from seed sources), primary production is usually low in undisturbed prairie..." (Knapp and Seastedt, 1986, p. 662).

Beneficial effects of prairie fire on True Prairie aboveground and belowground productivity are illustrated by experiments conducted at the University of Illinois' Trelease Prairie in Champaign County, Illinois (Table 1). As in other studies, burning increased plant nutrient content, including N, in the Trelease Prairie (Old, 1969). Thus, fire promotes SOC sequestration by increasing biomass and by increasing the proportion of this larger amount of biomass that will be converted to humus by increasing biomass nutrient content. Review of the literature shows that frequent burning increases root, invertebrate, and microbial biomass in prairie soils (Rice et al., 1998).

Fire converts biomass to long-lived SOC as charcoal — black carbon (BC). The literature shows that 20 to 25 percent of grass biomass C that has been in wildfire is converted to BC, and that 40 to 50 percent of tree biomass C is so converted to BC (Crutzen and Andreae, 1990) which is ubiquitous in soils and sediments. While humus (especially in organomineral form) helps give soils a black color (Duchaufour, 1978), the literature shows correlation between forest and grassland soil color to BC — the blacker the soil the higher its BC content (Schmidt and Noack, 2000). Illinois prairie soils were blackened by the annual burnings of the prairie. La Salle saw this in northern Illinois during the winter of 1680:

"La Salle's men saw this landscape in its most dismal state, for to add to the dreariness of winter, the Indians had been burning over the prairies in their annual buffalo hunts, and in many places there was nothing but a vast expanse of charred black, contrasting with patches of white snow" (Bakeless, 1961, p. 294).

Table 1. Average Living Biomass (g m^{-2}), Percent Biomass Increase over “No Burn” Condition, and Root-to-Shoot Ratio, Trelease Prairie, Champaign County, Illinois, 1961-1962.

Burn treatment	*Grass type*	*Living biomass*	*Biomass increase*	*Root*:shoot
Shoot				
No burn	Big Bluestem	332	—	
	Indian Grass	482	—	
Burn 2	Big Bluestem	361	8.73	
	Indian Grass	517	7.26	
Burn 3	Big Bluestem	956	188	
	Indian Grass	1,053	118	
Burn 4*	Big Bluestem	1,360	310	
	Indian Grass	1,536	219	
Root **				
No burn	Big Bluestem	894	—	2.69
	Indian Grass	784	—	1.63
Burn 2	Big Bluestem	1,111	24.3	3.08
	Indian Grass	944	20.4	0.83
Burn 3	Big Bluestem	1,237	38.4	1.29
	Indian	965	23.1	0.92
Burn 4*	Big Bluestem	1,310	46.5	0.96
	Indian Grass	1,029	31.2	0.67
Total **				
No burn	Big Bluestem	1,226		—
	Indian Grass	1,266		—
Burn 2	Big Bluestem	1,472		20.1
	Indian Grass	1,461		15.4
Burn 3	Big Bluestem	2,193		78.9
	Indian Grass	2,018		59.4
Burn 4*	Big Bluestem	2,670		118
	Indian Grass	2,565		103

Source: Hadley and Kieckhefer (1963).
Notes:
No burn = burned in 1943; Burn 2 = burned in 1943, 1952, and 1959; Burn 3 = burned in 1943, 1952, 1959, and 1961; and Burn 4 = burned in 1943, 1952, 1959, 1961, and 1962.
* Burn 4 averages are for 1962 growing season only.
** Data are for 0-35 cm root depth.

Blane (1969) noted in passing through southern Illinois from Vincennes, Indiana to St. Louis, Missouri in 1822:

“I was always forcibly struck by the melancholy appearance of a burnt Prairie. As far as the eye could reach, nothing was to be seen but one uniform black surface, looking like a vast plain of charcoal. Here and there, by the roadside, were bones of some horses or cattle, which had died in passing through, or the horns of some deer which had been killed. These, bleached by the alternate action of fire and rain, formed, by their extraordinary whiteness, a most remarkable contrast to the black ground on which they lay” (p. 190).

Hall (1837) gave this general characterization of the prairies of Illinois:

"In the winter, the prairies present a gloomy and desolate scene. The fire has passed over them, and consumed every vegetable substance, leaving the soil bare, and the surface perfectly black" (p. 76).

A century later the prairie soils of Illinois were still described as black (e.g., Telford, 1926, p. 1). Charcoal has been found to contribute up to 45 percent of SOC in grassland soils (Schmidt et al., 1999) and soil biota mix millimeter-sized BC throughout the soil profile (Carcaillet, 2001). Amounts of BC analyzed in soils under natural vegetation range from on the order of 1,000 kg ha^{-1} under boreal and temperate deciduous forests to more than 100,000 kg ha^{-1} under Mediterranean vegetation — the latter being a mix of grass and trees with high fire frequency (Carcaillet and Talon, 2001).

By increasing biological productivity BC also may contribute to SOC indirectly. Charcoal has been widely used throughout the world as a soil conditioner to increase crop and tree growth, improve germination, and reduce disease (Tryon, 1948; Goldberg, 1985; Kishimoto and Sugiura, 1985; Schmidt and Noack, 2000). Root growth in charcoal-amended soils is enhanced. Production of various legume crops is increased by 20 to 30 percent (Iswaran et al., 1979; Kishimoto and Sugiura, 1985). Exceptionally heavy nodulation has been reported for soybeans grown in charcoal-enriched soils, along with increased yield and N content of roots and shoots. This has been documented even for charcoal added to organic-rich mineral soils and peats. It has been hypothesized that charcoal sorbs agents toxic to rhizobia and other microorganisms of the rhizosphere, and that this effect is general to legumes (Chakrapani and Tilak, 1974; Rajput et al., 1983). The literature shows that charcoal in soil sorbs heavy metals, organic toxins, stimulates microbial activity, acts as a substrate for enhanced microbial growth, and generally stimulates N fixation, ammonification, and nitrification (Tryon, 1948; Kishimoto and Sugiura, 1985; Pietikainen et al., 2000; Schmidt and Noack, 2000). The literature further shows that prairie burning enhances productivity, root biomass levels, root turnover, and arthropods — the latter being especially active in incorporating surface BC throughout the soil profile (Lussenhop, 1976). Frequent presettlement fires in Illinois created a multi-level, positive-feedback system for sequestering SOC and enhancing soil fertility.

For example, the land between the two Miami Rivers of Ohio were characterized as black soils: the soil profiles exposed by stream cuts were "as black as on the immediate border of a coal mine" (Baily, 1856, p. 212), too rich to grow wheat. Excess fertility, principally N, in prairie soils was noted in Illinois Agricultural Experiment Station Bulletin 761, *Nitrogen Use and Behavior in Crop Production*, to be a widespread problem:

"Early Illinois settlers found millions of acres of soils rich in organic matter. As bacteria decomposed this material, nitrogen was converted from organic to inorganic forms, which became available for plant uptake. During the first decade of cultivation, the prairie soil was apparently too rich for wheat: the wheat tended to grow too tall and then fall over, or lodge, thus reducing grain yields" (Welch, 1979, p. 10).

In addition to enhanced N fixation induced by fire-produced BC — and thereby increased SOC sequestration — inorganic constituents of fire ash also enhanced N fixation by raising soil pH and by supplying concentrated amounts of nutrients which stimulate both symbiotic and asymbiotic N fixation. The pH of Illinois prairie soils is higher (less acidic) than that of equivalent forest soils (Fehrenbacher et al., 1984; Figure 3).

Fire ash is highly alkaline with a pH of 12 to 13 while lime has a pH of ~8 (Unger and Fernandez, 1990; Ulery et al., 1993; Someshwar, 1996; Vance, 1996; Chirenje and Ma, 1999).

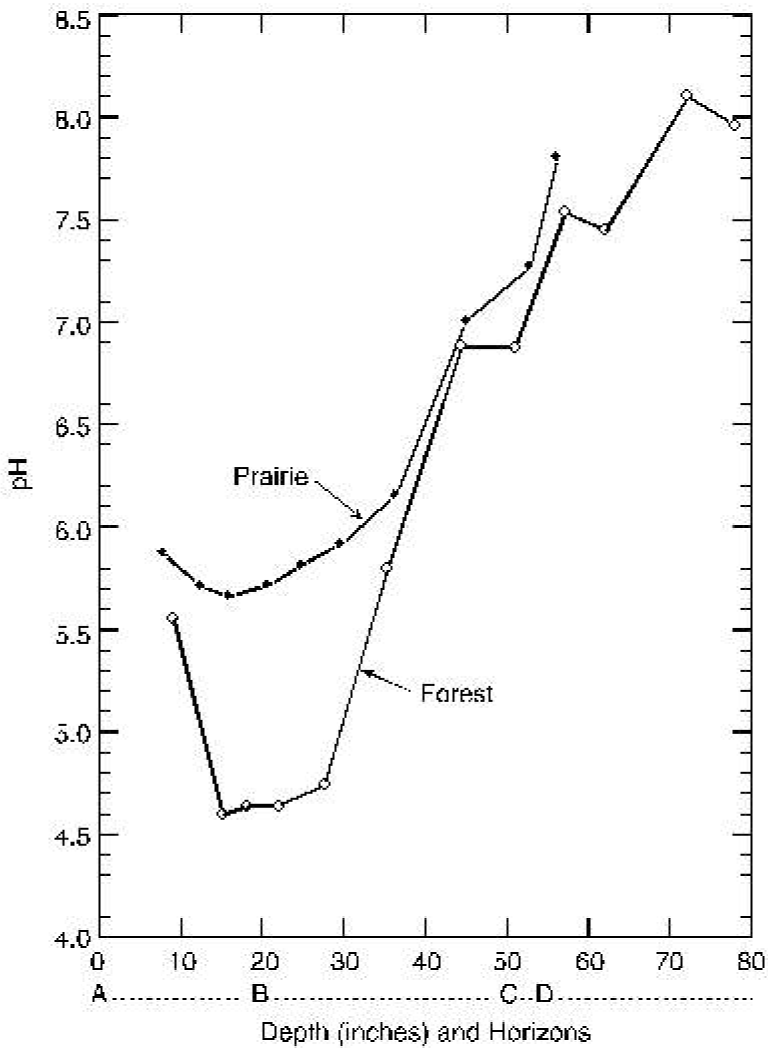

Figure 3. Comparison of the pH of forest and prairie soils of Illinois under identical soil-forming factors. Source: Jenny (1941).

Thus, frequent, intense fires of the presettlement era, by their indirect and direct effects on raising soil pH, enhanced N fixation by both free-living and symbiotic microorganisms, with free-living N-fixers being especially pH sensitive (McHargue and Peter, 1921; Waksman, 1937; Jenny, 1941; Thompson et al., 1954; Lodhi, 1977, 1982; Stark and Steele, 1977; Griffith, 1978; Cole and Heil, 1981; Schimel et al., 1985; Sprent, 1987, pp. 58-60; Mulder et al., 1997). Fire ash, unlike lime — the latter composed mostly of Ca carbonate ($CaCO_3$) — has plant nutrients in highly soluble oxide form (Unger and Fernandez, 1990; Ulery et al., 1993; Someshwar, 1996; Chirenje and Ma, 1999) that promote N fixation. It has been long known that P, K, and S enhance terrestrial N fixation (e.g, McHargue and Peter, 1921; Thompson et al., 1954; Walker and Adams, 1958; Mouat and Walker, 1959; Griffith, 1978; Cole and Heil, 1981; Zhao et al., 1999). Even though fire results in the loss of appreciable N to the atmosphere (Boubel et al., 1969; Risser and Parton, 1982; Crutzen and Andreae, 1990; Kuhlbusch et al., 1991; Sanhueza and Crutzen, 1998) fire increases soil N, legume content, and free-living N-fixing microorganisms of both prairie and forest floor (e.g., Heyward and Barnette, 1934; Greene, 1935; Garren, 1943; Gilliam, 1988; Niering and Dreyer, 1989; Tilman, 1996: Leach and Givnish, 1996; Hendricks and Boring, 1999).

On the Midwest prairie, fire not only increased aboveground and belowground biological productivity (Curtis and Partch, 1948; Hadley and Kieckhefer, 1963), it also increased nutritional content, e.g.:

"Higher N and P in plants and soils on burned sites than on unburned sites following fire reported by some workers... apparently results from the stimulation of biological processes, such as nitrification and mineralization, by burning..." (Dhillion et al., 1988, p. 707).

From this synthesis of the literature, it is clear that presettlement prairies were managed systems whose biological productivity, turnover, and SOC content were greater than that of 20th century prairie natural areas.

Fire and Forest

Away from dark, forested lowland swamps, presettlement forests were described as open and having a grassy, herbaceous, legume-rich groundcover in northern, central, and southern Illinois (Smith, 1881; Brendel, 1887; De Gannes; 1968; Hennepin, 1968; Schroeder, 1997, p. 35):

"The face of the country, from many miles back from the Ohio...[a]t the period of the first settlement in 1788, one dense, continuous forest covered the whole region, entirely unbroken by the hand of civilization, except for a small tract under the walls of Fort Harmar. The uplands presented a most enchanting appearance to the eye of the hunter or traveler. No brush wood then marred the fair beauty of the forest: but the view was extended from hill to hill amid the tall shafts of various species of tress without obstruction; while the mingled branches afforded no unapt resemblance to the interior of the dome of an immense temple.

"The yearly autumnal fires of the Indians, during a long period of time, had destroyed all the shrubs and under growth of woody plants, affording the finest hunting grounds; and in their place had sprung up the buffalo clover, and the wild pea vine, with various other indigenous plants and grapes, supplying the most luxuriant and unbounded pastures to the herds of deer and buffalo, which tenanted the thousands hills on the borders of the Ohio" (Hildreth, 1848, pp. 484-485).

The forests of Kentucky, south of the Ohio River and Illinois, were described as follows:

"The stories told of the abundance of grasses in the woods, are in many instances true. You frequently find beds of clover to the horse's knees.... There is also a species of vine, called the pea vine, from its producing a small pod, resembling that of the garden pea, of which both horses and cattle are extremely fond. These are scattered generally through the country, according to the different soil; but are not to be met with universally. The woods, however, afford abundant food for cattle; and in consequence of this abundance, the people pay very little attention to the making and improving pasture land" (Cooper, 1794, pp. 32-33).

Cooper's (1794) observations were typical of the early observations (McInteer, 1952).

Presettlement forests were different than the forested natural areas of today. Fire had shaped forest composition and ecology. Fire influenced tree species and density of trees, and maintained a rich ground layer of herbs, legumes, and grasses that supported abundant wildlife (Garren, 1943; Malin, 1953; Curtis, 1959; Iverson et al., 1989; Niering and Dreyer, 1989; Fralish et al., 1991). The timber of the region was described as "forming open park-like belts along the streams, which with great propriety have received the names of 'groves.' Here the species, as might be expected, more strongly recall the flora of the east, the resemblance extending not only to the trees and shrubs, but to the herbaceous species that flourish beneath their shelter" (Allen, 1870, pp. 582-583).

According to Marsh (1864, p. 120):

"In many parts of the North American States, the first white settlers found extensive tracts of thin woods, of a very park-like character, called 'oak openings,' from the predominance of different species of that tree upon them. These were the semi-artificial pasture grounds of the Indians, brought into that state, and kept so, by partial clearing, and by the annual burning of the grass. The object of this operation was to attract deer to the fresh herbage which sprang up after the fire. The oaks bore the annual scorching, at least for a certain time; but if it had been indefinitely continued, they would very probably have been destroyed at least. The soil then would then have been much in the prairie condition, and would have needed nothing but grazing for a long succession of years to make the resemblance perfect. That the annual fires alone occasioned the peculiar character of the oak openings, is proved by the fact, that as soon as the Indians had left the country, young trees of many species sprang up and grew luxuriantly upon them."

As summed up by Sauer (1956, p. 55):

"Our eastern woodlands, at the time of settlement, seem largely to have been in the process of change to park lands. Early accounts stress the open stands of trees, as indicated by the comment that one could drive a coach from seaboard to the Mississippi River over almost any favoring terrain."

The plants of the tallgrass prairie of the Prairie Peninsula are not the result of encroachment of grasses from the west, but rather, are the plants of the forest floor of the eastern forest. The prairie developed by removal of trees and survival of their understory plants (Gleason, 1922; Gleason and Cronquist, 1964; Martin, 1975; Graham and Lundelius, 1984).

From this synthesis of the literature, it is clear that presettlement forests were managed systems whose biological productivity, turnover, and SOC content were greater than that of modern forested natural areas.

Some Effects of Animals on Prairie and Forest

A fundamental tenet of modern evolutionary theory is that both physical and biotic changes trigger evolutionary changes. The coevolution of large mammalian herbivores and the grasses reportedly began 45 to 55 million years ago during the Eocene Epoch. As a response to intense pressure upon brush and trees by browsers, the geologic record indicates that woody grasslands appeared and further developed in North America 20 million years ago. As grasses appeared, so did animals to graze them. Bison and sheep graze grasses close to the ground and began arriving from Eurasia 1.6 million years ago. Old *Stipa* sp. and other grasses gave way to sod-forming grasses — e.g., bluestems, Indian grass, gramma grass, and buffalo grass — which could bear such grazing pressure (Stebbins, 1981). As the plants of the tallgrass prairie of the Prairie Peninsula are the plants of the forest floor of the eastern forest, it is not surprising that both the prairies and forests of Illinois were animal-rich habitats:

"A considerable portion of the above ground biomass of a prairie was consumed each year by the grazing of a wide range of grazing animals, such as bison, elk, deer, rabbits and grasshoppers. This grazing was an integral part of the prairie ecosystem.... Grazing increased growth in prairies, recycles nitrogen through urine and feces, and the trampling opens up habitat for plant species that prefer some disturbance of the soil" (Illinois Natural History Survey, 1999).

Bakeless (1961, pp. 308-309) noted:

"The forest fires, however terrible, had one advantage. They decreased the density of the forests and thus encouraged the deer, so that the Indians were likely to kindle fires and let them run whenever they wanted more deer — which, as one warrior explained, were their cattle. As a result, the animals were everywhere. Christopher Gist, exploring the Middle West [in the 1750s], notes casually: 'Being in Want of Provisions, I went out and killed a Deer.' It was as simple as telephoning the butcher. Hunters rarely took anything but the haunches, the choicest meat."

The great number of large grazing animals living in the prairie and forests helped keep them in an open condition and greatly influenced the growth and composition of the prairie and the prairie-like forest understory (e.g., Borowski et al., 1967; Stebbins, 1981; Owen-Smith, 1987; Gibson, 1989; Savage, 1991; Weigl and Knowles, 1995; Coppedge and Shaw, 1997).

As noted by the Illinois Natural History Survey (1999), grazing increases biomass production. Using mowing and raking to simulate the effect of grazing, scientific studies, including those conducted at the Trelease Grassland, indicate that the effect of grazing on biomass production is intermediate between burning and not burning (Old, 1969; Risser et al., 1981; Risser and Parton, 1982). Overall, research indicates that grazing of tallgrass prairie increases both aboveground and belowground plant productivity (Risser et al., 1981, pp. 176-184). Furthermore, disturbance — manuring, grazing, and pocking of the turf by hooves — promotes increased plant heterogeneity, particularly legume growth (e.g., O'Connor, 1981; Bauer et al., 1987; Illinois Natural History Survey, 1999).

By increasing biomass production, grazing increases sequestration of SOM, SOC, and soil organic nitrogen (SON) by increasing C produced by Illinois' ecosystems:

"Soil bacteria, the agents of decomposition, use carbon mainly as fuel and nitrogen as building material for their bodies.... Fresh organic matter is characterized as a rule by a large amount of carbon in relation to nitrogen. It has a wide carbon-nitrogen ratio, in other words; or so far as the bacteria are concerned, a wide ratio of fuel to building material. Such fresh material — straw, for example, — may have a ratio that is too wide.... The carbon will then be rapidly used up as fuel while the nitrogen is held or treasured without appreciable loss.... Thus when decay has proceeded to the point where the carbon-to-nitrogen ratio is significantly decreased, a residue of a more stable nature is produced. Thereafter the carbon-nitrogen ratio is narrower and remains more constant. This corresponds more nearly to the condition that holds in the case of the organic matter in virgin soils" (Albrecht, 1938, pp. 355-356).

By favoring the growth of legumes over other less N-rich biomass, grazing increases sequestration of SOM, SOC, and SON:

"The amount of increase in [soil] organic matter corresponds, in the main, to the amount of nitrogen available. The extra carbon in the fresh material is lost from the soil. Thus when soils are given straws, fodders, and similar crop residues of low nitrogen content, only small increases in soil organic matter can result—in the main, only as large as the added nitrogen will permit.

"The restoration of soil organic matter, then, is a problem of increasing the nitrogen level or using nitrogen as a means of holding the carbon and other materials. This is the basic principle behind the use of legumes as green manures" (Albrecht, 1938, p. 356).

Observers and scientists from the present (e.g., Bol et al., 1999) and dating back to Darwin, and earlier, have attributed the great fertility (and SOC content) of grazed land to be at least in part due to the manuring which grazers effect on the soil itself, a natural form of "scientific farming" of the landscape akin to humus production by the Old World farmer using straw, dung, and urine (Roe, 1951, pp. 497-498):

"Small amounts of added nitrogen may in this way make possible the use of large amounts of carbonaceous matter in restoring the soil. Thus the European farmer first 'makes' his manure by composting the fresh straw-dung mixture from the barn and then treats it intermittently with the nitrogen-bearing liquid manure or urine from the same source and the nitrogen-rich leachings from the manure pit. He does not consider the fresh, strawy barn waste manure in the strictest sense until the surplus carbon has been removed through the heating process, and the less active manure compounds become similar to those of the soil organic matter.... The manure making of the Old World farmer turns the miscellaneous straw-dung-urine mixture, of highly variable value, into a standardized fertilizer for specific use" (Albrecht, 1938, p. 356).

Whereas the Old World farmer made his organic fertilizer, Native Americans manipulated the ecosystem to make theirs. The animals manured the landscape by trampling their dung and urine into the soil — mixing dung and urine with “straw” and trampling this mix into the ground. A whole subterranean ecology of insects and other soil animals mixed the dung down into the soil from below (Hole, 1981).

In presettlement Illinois, Hennepin and company, “started down the [Illinois] river at the end of February, 1680. The Illinois broadened and deepened as they descended, flowing in that flat land.... ‘The soil,’ Hennepin noted, ‘looks as if it had already been manur’d.’ It was, in fact, the result of centuries of the slow rotting of prairie vegetation, made still more fertile by the ‘chips’ dropped through the ages by millions of buffalo, and fertilized at last with their bones. The constant moisture had favored decomposition. The country was, in fact, one vast compost heap. No wonder that it includes today some of the best farm land of the nation” (Bakeless, 1961, p. 297).

The contribution of manure from grazing animals is furthered supported by the famous Lawes and Gilbert experiments, at the world’s oldest continuous agricultural experiment station, Rothamsted in England. In the 19th Century they came up with the remarkable finding that while cultivated land lost N, pastured land gained an average of 49 kg N ha^{-1} yr^{-1} (Snyder, 1905, pp. 111-112).

Turning to the more recent studies conducted on the American prairie, analysis of paired ungrazed and grazed tallgrass prairie showed higher N content in tallgrass prairie vegetation and higher concentrations of total soil N, soil nitrate-nitrogen (NO_3-N), and ammonium-nitrogen (NH_4-N). This occurred in spite of grazing-increased N loss to ammonia (NH_3) gas volatilization and N loss to harvesting of the cattle themselves (Risser and Parton, 1982). These two forms of N loss are significant. The harvesting of cattle from the land represents 25 percent of the total N eaten by the cattle (Aldrich, 1980, Figure 4.4) and dairy manure has been determined to lose anywhere from 61 to 99 percent of its NH_4-N within 5 to 25 days after being on the surface (Lauer et al., 1976).

While the manuring of abovegound biomass was obviously great, the manuring of belowground biomass was obviously greater because most biomass produced by prairies and prairie-like forest floors was belowground biomass; and this greater biomass was consumed and converted to manure by soil microfauna and macrofauna. The soil biology literature shows that prairie soils have by far the highest quantity of microorganisms and microfauna of any soil type, for example, having 10 to 100 times the bacterial biomass of forest soils. Prairie soils macrofauna is 2 to 10 times that of forest soils. It appears that more animal biomass lives in prairie soils than on them (Hole, 1981). Prairie soils biomass turnover is very rapid, averaging 1.2 times per year (Brady, 1974, pp. 114-115; Ugolini and Edmonds, 1983, pp. 198-199). Furthermore, root turnover is much higher than indicated by changes in root mass as macrofauna (invertebrates) eat roots, enhance root decomposition, and enhance rate of nutrient cycling and root growth. Thus, root turnover is much higher than indicated by changes in root mass (Rice et al., 1998), especially in prairie soils:

“The rate of energy turn-over in grassland soil is high compared, for example, with that of a forest. This means that organic material, derived from herbaceous vegetation, is broken down very quickly by large saprophages, such as earthworms, molluscs, millipedes and woodlice, and by microfloral decomposers, such as bacteria. However, in ‘managed’ systems where fertilizers are added to the soil to promote plant growth, these smaller animals become much more important and their contribution to energy turn-over may exceed that of the larger forms...” (Wallwork, 1976, p. 55).

As noted by Byers et al. (1938 p. 963), biological activity in the soil also results in chemical and physical mixing:

“Two of the chief functions of plant and animal life, so far as soil profile development is concerned, are the furnishing of organic matter for the soil and the bringing in of plant nutrients from the lower layers to the upper ones.”

Not surprisingly, the literature shows that soil arthropod abundance is correlated to quantity of SOM. And, not only did fire and grazing enhance SOM, they enhanced arthropod abundance (Lussenhop, 1976). Fueled by high rates of subsurface primary production and microbial secondary production, manuring of the soil by soil animals and its spread throughout presettlement prairie soils by pedoturbation undoubtedly was intense. Microfauna and macrofauna physically turnover prairie soils much more rapidly than they do their forest counterparts (e.g., Curtis, 1959, pp. 279-260; Ugolini and Edmunds, 1983). For example, not counting downward and within-soil mixing, moles may bring up as many as 55 metric tons ha^{-1} yr^{-1} of soil to the surface (Abaturov, 1972; Hole, 1981, p. 93).

Pedoturbation by the common eastern mound-building ant (*Formica exsectoides*) in a grassy clearing of forest in southern Wisconsin was researched by Salem and Hole (1968). The soil (Dubuque silt loam) was formed under oak savannah from 25 to 100 cm of loess underlain by limestone residuum. It was found that in 2.2 years the ants had reworked the soil to 160 cm and, not counting downward and within-soil mixing, moved to the surface 13,600 kg soil ha^{-1} yr^{-1} (Salem and Hole, 1968; Ugolini and Edmunds, 1983, p. 218). This estimate does not include pedoturbation by smaller subdominant mound-building species, the contingent of subterranean ant species, and other living agents of soil pedoturbation common in prairie and prairie-like environs (Trager, 1990).

Pedoturbation by the prairie ant (*Formica cinerea* sp.) — which once dominated Illinois' mesic prairies (Park et al., 1953; Peterson et al., 1998) — was researched in mesic tallgrass prairie at the University of Wisconsin's Curtis Prairie in Madison, Wisconsin. The soil was Tama silt loam (Baxter and Hole, 1967), the modal prairie soil of the Upper Mississippi Valley (Smith et al., 1950). *Formica cinerea* sp. was calculated to completely mix the top 150 cm of Tama soil in 600 to 1,200 years (Baxter and Hole, 1967; Ugolini and Edmonds, 1983, p. 218). It was estimated that the top 60 cm of Tama soil gets mixed by microfauna and macrofauna every 100 years (Baxter and Hole, 1967; Buol et al., 1980, p. 261).

Research on pedoturbation in heavy wet grassland soil in England (Green and Askew, 1965) appears relevant as this English soil ecosystem is similar in some critical respects to those of central Illinois (Fehrenbacher et al., 1984) and the Curtis Prairie (Baxter and Hole, 1967). This English grassland soil has a fluctuating watertable that drops down to 1 to 2 m during the dry season and comes within 15 cm of the surface, or above the surface, seasonally. Like our moist, tallgrass loessal prairie soils, this English grassland soil cracks extensively and deeply upon drying, and expands and becomes massive when wetted. Ponding is common when it rains. Nevertheless, wet drainage through old root channels, extensive ant and worm holes, and holes of *Gammarus* sp. and millipedes continued to depths greater than 150 cm — the maximum depth of soil examined (Green and Askew, 1965).

Mixing and manuring of presettlement prairie soils by microfauna and macrofauna undoubtedly was intense and increased subsoil SOC content beyond what roots alone could provide.

From this synthesis of the literature, it is clear that presettlement prairies were managed systems whose biological productivity, turnover, and SOC content were greater than that of modern natural area analogs.

Soil "Aging"

The heterogeneity of the Earth's surface processes results in soils of widely varying effective ages. From this the aging sequence that varying soil types undergo is inferred. The inferred aging sequence of the genesis of various Illinois soil types is called the Illinois soil development sequence (also called the Illinois soil maturity sequence). Soil genesis is important because it governs SOC sequestration. When erosion exposes rock and other geologic materials at the Earth's surface, they become subject to corrosive forces — physical, chemical, and biological — called weathering, that turn them into soils. Soil aging involves the extraction and removal of mineral elements and nutrients by weathering. Most of the weatherable elements and nutrients in juvenile soils are still retained in the crystal structures of their parent materials minerals. Stores of plant-available nutrients have not yet reached their peak amounts.

Biological activity accelerates mineral weathering and the soil-forming process (Jenny, 1941; Ugolini and Edmonds, 1983, p. 193). The latter, as stated in the language of Hopkins (1910), is that biological activity accelerates soil aging. As soils age, easily weatherable minerals are lost first. Some released nutrients are lost from the soil; some are stored in plant-available form as SOM, easily-weatherable secondary minerals, and on ion exchange sites. Over time, the soil's bank of SOM, SOC, and plant-available nutrients grows to maturity, i.e., achieves its maximum. It may be said that Native American land-use practices accelerated soil maturation by stimulating biological activity.

Gradually, more and more of the soil's declining store of mineral nutrients are weathering-resistant, mineral residue. At sometime during the aging process, the natural rate of nutrients released by mineral weathering no longer keeps up with the natural rate of soil nutrient loss. As soils age past their peak productive years, post-mature soils become more acidic as they lose base cations, such as Ca^{2+} and Mg^{2+}. They also lose P and K and biological productivity decreases. It is at this point that soils decline and begin to grow old (post-mature). Soil ecosystems use up their banked stores of nutrient-bearing SOM and SOC decreases. With increased acidity and decreased P and K, N fixation also decreases. Because soil humus requires N, P, K, and S (Stevenson, 1994; Krug and Winstanley, 2000), all three factors synergistically interact to limit SOC sequestration (Figure 1). Fine soil aggregates produced by plant and animal pedoturbation decrease as soils become progressively more post-mature. Soil structure becomes more massive, and SOM becomes less exposed to (more protected from) decomposition by the ever-diminishing weathering capacity of biological activity.

Geologic parent material is also very important to soil genesis and SOC sequestration. Geologically, much of Illinois is mantled with loess — fine, wind-blown silt (Smith, 1942; Flint, 1971, pp. 255-261; Fehrenbacher et al., 1984). Fine-textured soils tend to have greater amounts of weatherable mineral nutrients, greater water retention capacity, more organic-matter-protective fine mineral grains and, therefore, contain greater amounts of C, N, S, and better soil aggregation than coarser-textured soils (Jenny, 1941; Brady, 1974; Fehrenbacher et al., 1984; Oades, 1988; Parton et al., 1988; Li et al., 1994).

Depth of soil-forming geologic parent material, especially loess, is important to the Illinois soil development sequence. Illinois had a number of sources for loess and depth of loess decreased with distance from source. The thinner the loessal cap, the more rapidly the soil weathers (ages), and the quicker it loses mineral nutrients, which, in turn, often affects the amount of C, N, and S held in the soil. These soils have a shorter life span; thus, their "effective age" (Harlan et al., 1977) is greater than would be expected from their chronological age. All else being equal, the older the loessal or glacial till deposit (Wisconsin versus Illinoisan Ice Ages), the more weathered and/or nutrient-poor the material (Hopkins, 1910; Bray, 1937; Bushnell, 1944; Smith et al., 1950; Jones and Beavers, 1966; Harlan and Franzmeier, 1977; Harlan et al., 1977; Fehrenbacher et al., 1984, 1986):

"The brown silt loam prairie soil of the early Wisconsin glaciation is the most common type of the greatest soil area of the Illinois Corn Belt. Two million pounds [909,091 kg]of this surface soil contain as an average:

Potassium ....36,250 pounds [16,477 kg]
Magnesium ....8,790 pounds [3,995 kg]
Calcium ....11,450 pounds [5,205 kg]
Phosphorus ....1,190 pounds [541 kg]

"The older gray silt loam prairie, the most extensive soil of Southern Illinois, contains in two million pounds of soil:

Potassium ....24,940 pounds [11,336 kg]
Magnesium ....4,690 pounds [2,132 kg]
Calcium ....3,420 pounds [1,555 kg]
Phosphorus ....840 pounds [382 kg]

"These data represent averages involving hundreds of soil analyses..." (Hopkins, 1913, pp. 10-11).

Also, it has long been recognized that humans can act as geologic agents to reverse the aging process and rejuvenate soils by adding nutrients to increase fertility and increase soil C and N content. Anthropogenic rejuvenation is especially pronounced when nutrients are added to soils of nutrient-poor geologic terrains — poor in P and other mineral nutrients as a function of inherent composition of parent material or because of advanced stages of weathering (Hopkins, 1910; Jenny, 1941; Walker and Adams, 1958, 1959; Walker et al., 1959; Cole and Heil, 1981; Haynes and Naidu, 1998). Conversely, human activities can accelerate soil aging by tillage practices that break down biopeds and expose SOM to enhanced weathering, by accelerating erosion of rich topsoil, and by harvest removal of nutrients.

As prairie soils age past maturity, pedoturbation and the resulting soil aggregation decrease to the point that the movement (eluviation/illuviation) of clay-sized mineral particles from the topsoil down into the subsoil proceeds — similar to the eluviation/illuviation of forest soils (Shrader, 1950; Smith et al., 1950; Arnold and Riecken, 1964; Geis et al., 1970; Fehrenbacher et al., 1984). Such aging can proceed to the point that dense, acid claypans develop in the subsoils of Illinois prairie soils. In addition to the biologically unfavorable texture and chemistry, decreasing depth to a perched or real watertable limits root growth and overall biological productivity (Hopkins, 1907, 1910; Bray, 1937; Bushnell, 1944; Smith et al., 1950; Jones and Beavers, 1966; Harland and Franzmeier, 1977; Harlan et al., 1977; Fehrenbacher et al., 1984, 1986). These conditions also limit the depth and frequency of subsoil excavation by soil fauna (Baxter and Hole, 1967). Decreasing pedoturbation also manifests itself in soil structure; the open crumb-type aggregate structures produced by roots and their associated rhizosphere as well as by soil animals is replaced by other types of soil structure, platy and prismatic peds with clay skins and massive soil structure (Fehrenbacher et al., 1984). The reduced amount of SOM and SOC in post-mature (old) subsoils is thus more protected from the decomposition processes than in the equivalent, more SOM- and SOC-rich, younger soils.

From this synthesis of the literature, it is clear that soil aging is affected by climate, biology, and human activities. The latter can act to hasten soil aging or reverse the aging process and rejuvenate the soils through control of the vegetation on the soil and addition of nutrients into the soil.

Rapidity of Prairie and Forest Soil Conversion

As indicated by the observations made in the previous section, "**The History and Genesis of Soils and Vegetation in Illinois**," there were two centuries of observations of forest and prairie ecosystems prior to European settlement. These were made by explorers, scientists, surveyors, and pioneers and are applicable to soil-forming factors which affect SOC sequestration. European observers watched the effects of Old World diseases which reduced Native American populations by an estimated 90 percent. Observations were made as the survivors of disease fled in advance of European settlement and those who chose to remain behind were removed by military force and/or by treaty (Flint, 1832; Kip, 1846; Hildreth, 1848; Marsh, 1864; Wilcox, 1904; Buck, 1912; 1917; Quaife, 1918; McComb and Loomis, 1944; Roe, 1951; Curtis, 1959; Bakeless, 1961; Cooper, 1961; Angle, 1968; Sutton, 1976; Seno, 1985; Butzer, 1992; Denevan, 1992a, b; Krug and Winstanley, 2000). Surveys were made, during the first half of the 1800s and into the second, of Illinois lands acquired from Native Americans in preparation of European settlement (e.g., Iverson et al., 1989; Sulaway, 2002). As reviewed by Krug and Winstanley (2000), even after various areas of Illinois underwent European settlement, significant areas of land remained undeveloped and scientists continued to observe the remaining native, natural area ecosystems. For example, even by 1900, much prairie and forest still remained as only 4.05 million ha of cropland existed in Illinois' 14.5 million ha of land. Another 5.26 million ha of land had yet to be put to the plow to make the 9.31 million ha of cropland we have now (Krug and Winstanley, 2000, p. 4). Thus, observation and study of prairie and forest vegetation was ongoing between the early French explorers of the 1670s to the present (Imlay, 1797; Flint, 1832; Shirreff, 1835; Hall, 1837; Short, 1845; Kip, 1846; Hildreth, 1848; Bailey, 1856; Marsh, 1864; USDA, 1876; Allen, 1870; Reynolds, 1879; Smith, 1881; Brendel, 1887; Shaler, 1891; Christy, 1892; Michaux, 1904; Wilcox, 1904; Buck, 1912; 1917; Gleason, 1913; 1922; Sauer, 1916; Vestal, 1918; 1931; Forbes, 1919; Telford, 1919; 1926; Sampson, 1921; Shull, 1921; Woodward, 1924; Chavannes, 1941; McComb and Loomis, 1944; Leopold, 1949; Hewes, 1951; Roe, 1951; Stewart, 1951; Park et al., 1953; Evers, 1955; Hadley and Kieckhefer, 1963; Larimore and Smith, 1963; Mills et al., 1966; Angle, 1968; Blane, 1969; Old, 1969; Fentem, 1978; Leitner and Jackson, 1981; Risser et al., 1981; Haugen and Shult, 1983; Seno, 1985; Ebinger, 1986; Betz, 1986; Packard, 1988; Betz and Lamp, 1989; Harrington and Leach, 1989; Trager, 1990; Fralish et al., 1991; Kucera, 1992; Leach and Givnish, 1996; Schroeder, 1997; Peterson et al., 1998; Illinois Natural History Survey, 1999; Bonnicksen, 2000; Esarey, 2000; Krug and Winstanley, 2000; Teed, 2000; Illinois Department of Natural Resources, 2001; Prairie Frontier, 2002). The observations of three centuries of prairie and forest ecosystem changes provide a rich resource to research the speed and magnitude by which the biotic component of soil formation may influence

SOC sequestration — an approach used by Krug and Winstanley (2000) to estimate how changes in prairie, forest, and other native ecosystems influenced water quality.

Once land was taken out of Native American stewardship, prairie could rapidly convert to forest:

"In humid parts of the tall-grass prairie, protection from fire and/or moderate grazing by large herbivores hastens deterioration, as evidenced by encroachment of woody species and decline and production of grasses within about 3 to 5 years" (Kucera, 1992, p. 260).

The U.S. Department of Agriculture (USDA, 1876) reported that in Illinois:

"Whenever the fires on prairies have been stopped for a few years, a young, spontaneous growth [of trees] covers the ground" (p. 310).

There is evidence that postsettlement conversion of prairie to forest had converted prairie soil to forest soil by the early 20th Century. Prairie is reported to have been essentially nonexistent in the seven southernmost counties of Illinois in presettlement times and along the 190-km route in southernmost Illinois along which General Clark led his Revolutionary Army in 1778 (Reynolds, 1879; Woodward, 1924; Telford, 1926; Vestal, 1931; Fentem, 1978; Leitner and Jackson, 1981; Iverson et al., 1989; Fralish et al., 1991; Suloway, 2002). Yet General Clark reported that most of the army's trek through southernmost Illinois was through prairie, not forest. For six days Clark led his army from Fort Massac on the Ohio River (Massac County, Illinois) in a line northwest to Kaskaskia. For four of those six days Clark's troops marched in open, sun-baked prairie. The four days march through prairie was nerve wracking because the prairie horribly exposed Clark's troops to any enemy that might have been watching for many miles around (Bonnicksen, 2000, p. 330). Clark described this presettlement southernmost Illinois landscape as:

"Extending beyond eyesight are large prairies covered with buffalo and other game, varied by groves of trees that appear like islands in the sea. With a good eyeglass you can see all the buffalo for over a half a million acres..." (Seno, 1985, p. 224).

Others during the late 1700s found prairie in southernmost Illinois where none was reported to be mapped in 1804 to 1820 (Iverson et al., 1989; Suloway, 2002). French Botanist Andre Michaux (1904) found a number of prairies while making excursions off and along the low road between Kaskaskia and Fort Massac. Collet (1968) traveled through ~ 80 km of prairie in southernmost Illinois, much of which was not mapped as prairie in 1804 to 1820. In 1787 General Harmar conducted a land survey for the War Department between Vincennes and Kaskaskia. Whereas in 1804 to 1820 most of the land along this transect was mapped as forest, Harmar found most of it to be prairie. In the 1700s, there was a vast amount of True Prairie in southernmost Illinois south of Kaskaskia which, except for the swampy forests along the Ohio River, appears to have been largely prairie (Smith, 1881).

Reynolds (1879) wrote of the nature of Illinois and of the changes he observed between around 1800 and 1850:

"All south of a line extending from Kaskaskia by Perry and Franklin Counties, to White County on the Wabash River, is a timbered country, and north of it mostly the prairies intermix with timber.

"I have witnessed the growth of the forest in these southern counties of Illinois, and know that there is more timber in them now than there was forty or fifty years before" (p. 26).

These observations are consistent with replacement of prairie by forest after the removal of Native American presence, and with the maturation of the southern forest between 1800 and 1850 — most of this period being when the non-Native American population of Illinois was concentrated in southern Illinois and relying heavily on wood for fuel and building materials.

Removal of Native American presence not only altered the vegetation soil-forming component of southernmost Illinois, but also its animal life.

In the early 1700s, buffalo were plentiful in southernmost Illinois. It was here where the first large, commercial buffalo-hunting operation in the New World was located. This operation, headquartered in Pulaski County, was started by the French in 1703 — long before Daniel Boone began exploring eastern Kentucky in 1767. Buffalo hides were brought here from an average of 80 km to go through the 7-year-long tanning process. Strategic caches for hides were located along the Cache River and Big Muddy River. There was an appreciable Native American presence. In 1704, Native Americans massacred all but one of the 100 French buffalo hunters. Nevertheless, in 14 months of hunting, the French hunters had killed, collected, and transported 13,000 buffalo hides for processing (Moyers, 1931).

In 1712, Father Marest reported large numbers of buffalo feeding on both sides of the Ohio River along southernmost Illinois (Kip, 1846, p. 197).

Roe (1951, p. 232) noted that Michaux saw buffalo in southernmost Illinois in the 1790s but nothing like the numbers reported 30 years earlier.

Less than a century later, Cory (1912, p. 92) reported that:

"Audubon and Bachman say, 'In the days of our boyhood and youth Buffaloes roamed over the small and beautiful prairies of Indiana and Illinois and herds of them stalked through the open woods of Kentucky and Tennessee, but they have dwindled down to a few stragglers, which resorted chiefly to the [Kentucky] Barrens toward the years 1808 and 1809 and soon entirely disappeared.' "

Allen (1876) not only recognized the existence of bison in southernmost Illinois, but also that the large prairie in western Kentucky was an extension of the prairie of southernmost Illinois. As soon as the Amerinds were driven out, that these prairies sprang up into timber "and are now densely wooded" (p. 235).

It appears that the Native American influence of even the early 1700s was already in decline as Native Americans were suffering the ravages of Old World disease and war. Indeed, early French missionaries — Hennepin and Marquette — stated that, by 1670, the Illinois had been at war with their neighbors (Native Americans fleeing from European settlement further east) over buffalo and that buffalo numbers were already relatively scarce compared to what they had been because all parties were continually hunting them (Roe, 1951, pp. 650-651).

After the Revolutionary War, Native American presence in southern Illinois was slight (Smith, 1881; Michaux, 1904; Clark, 1912; Buck, 1917; Collett, 1968; Seno, 1985), less than 1,500 Amerinds (Imlay, 1797, p. 290). In 1787, Union, Johnson, Pope, Hardin, Alexander, Pulaski, and Massac Counties became the "Soldiers Reservation" in which battle-hardened Indian fighters received land in lieu of pay (Moyers, 1931). Not surprisingly, by 1803, Native Americans were completely out of Illinois south of the line through Vincennes (Buck, 1917, p. 40). However, there were still some Native Americans further north in Illinois as late as the 1830s. Between 1800 and the 1830s three Indian Wars were waged in central and northern Illinois and the inhabitants of Peoria and Chicago were massacred:

"In 1833, when the first squatters appeared [in Kane County], Chicago was but a frontier outpost, in that year was incorporated as a village with two or three hundred inhabitants—many of them half-breed French and Indian..." (Wilcox, 1904, p. 632).

Also, in 1833:

"Chicago consists of about 150 wood houses.... Almost every person I met regarded Chicago as the germ of an immense city.... At the time of visiting Chicago, there was a treaty in progress...and it was supposed nearly 8,000 Indians [were present].... The forests and prairies in the neighborhood were studded with the tents of the Indians, and numerous herds of horses were browsing in all directions" (Shirreff, 1835, pp. 226-227).

Flint (1832, p. 330) reported considerable Native American presence in northern Illinois:

"A considerable number of Sacs and Foxes still inhabit the banks of the Rock River, or its waters."

Early observations show that forest expansion in Illinois preceded European settlement (Gleason, 1913).

Massive forest expansion also occurred in Iowa prior to European settlement (McComb and Loomis, 1944).

In southernmost Illinois, in the absence of Native American presence, large areas of prairie converted to forest on the order of decades. Soil scientists of the early 20th Century characterized soils which were under prairie until the end of the 1700s as forest soils. This indicates that prairie soils can convert to forest soils on the order of a century. A remarkable observation, especially in light of the morphological changes that would have to take place in soil.

Tama silt loam and Fayette silt loam are the modal prairie and forest soils, respectively, of the Upper Midwest (Smith et al., 1950). Both are formed from the same parent material — geologically-young (Wisconsin) loess — and have the same amount of the same end-product clay minerals produced by mineral weathering. Nevertheless, these soils do have remarkable differences. Smith et al. (1950, pp. 165-171), report that the prairie soil had about twice the SOC and N of the forest soil, was darker in color, and had a soil structure (soil aggregation) developed by very active pedoturbation. Clay mineral distribution was uniform throughout the profile of the prairie soil and increased with depth in the forest soil. Thus, the surface of the prairie soil has more clay than the forest soil:

"The differences are thought to represent differences in eluviation under grass and forest, but the reasons for the differences are unknown" (Smith et al., 1950, p. 172). Such differences in soil profiles are used to characterize soils as either forest or prairie soils.

Representative profiles of Missouri prairie and forest soils developed from loess show the same thing. The eluvial (A) horizon of the representative forest loess soil (Menfro silt loam) has 9.9 percent clay, while its illuvial (B) horizon has 31.2 percent clay. The A horizon of the representative prairie loess soil has 29.7 percent clay, and its B horizon has 29.1 percent clay (Shrader, 1946). The results of Peterson (1946) and Arnold and Riecken (1964) are similar to those of Shrader (1946) and Smith et al. (1950) regarding eluviation/illuviation differences of prairie and forest soils.

However, as prairie soils age and become post-mature, dense claypans develop, eluviation/illuviation becomes pronounced, and depth of perched or real watertable decreases (Shrader, 1950; Baxter and Hole, 1967). Morphological differences between post-mature prairie and forest soils decrease (e.g., Hopkins, 1910; Smith et al., 1950; Fehrenbacher et al., 1984), as do differences in SOC and soil N (e.g., Hopkins, 1910; Figure 2). Given that 20th Century soil scientists apparently were unable to distinguish between soils whose vegetation changed from prairie to forest some 100 years earlier, it appears that the 30, or more, percent greater SOC in the top 1 m of these post-mature prairie soils (Hopkins, 1910, Figure 2) was lost during the century of forest occupancy.

The observation of rapid morphological transformation of post-mature prairie soil to forest soil also was observed by Marbut — the Father of modern American soil science. He made this observation while guiding the world's preeminent soil scientists through the United States during the *First International Congress of Soil Science*:

"The soil examined here is predominantly a soil developed under grass cover but which has, over considerable part of the region, been invaded in recent times by forest. It was part prairie and part forest land, when first occupied a little less than 100 years ago.... The American workers interpret these western Ozark soils as Prairie soils, now in an advanced stage of what may be degradation. They are in progress of development into Forest soils, and when that stage is reached will be members of the great Brown soil group similar to those of the mid-latitude belt of the United States extending from the Chesapeake Bay Region westward to the prairies. This stage of development has been reached over a large part of this Ozark Region, especially in the moderately hilly belts lying adjacent to the streams " (Marbut, 1928, p. 61).

Given the greater morphological differences between young (Wisconsin/Holocene) prairie and forest soils, more than the century time scale appears to be required for soil conversion, e.g.:

"The reverse process, the regradation of a gray-brown Podzolic soils into a Prairie soil, is theoretically possible so long as chemical weathering has not been so severe that the primary calcium bearing minerals have been destroyed. There are extensive areas of Prairie soils in eastern Iowa and northwestern Illinois which are now correlated with the Tama series. In these the B horizon has both the structure and the moderate-to-heavy coating of light grey silt on the structural aggregates which are normally considered characteristic of Gray-brown Podzolic soils. No better explanation has been advanced for these grey coatings than that they are relict characteristics of a former Gray-brown Podzolic soil which has been converted into a Prairie soil by the encroachment of grass on the forest" (Smith et al., 1950, p. 169).

Arnold and Riecken (1964, p. 352) state:

"The general location of Brunizem soil sites with observed grainy gray peds are shown.... These sites occur in the Iowa drift and adjacent loessal areas in eastern and northeast Iowa, principally the Kenyon-Floyd-Clyde (CC) and the Tama–Muscatine (TM) soil association areas shown....

"The Brunizem soils throughout the rest of Iowa characteristically do not have grainy ped coatings in any part of the solum. However, coatings have been observed at depths greater than 30 inches [76 cm] in some Brunizems located adjacent to major streams. Such sites are on loess-covered stream terraces or elevated alluvial fills and commonly trees are nearby. This suggests that trees, present or past, may be related to the presence of coatings at these sites. Also, coatings may occur in Brunizems that intergrade to Gray-Brown Podzolic soils. Observations in Taylor and Lucas Counties revealed that grainy gray ped coatings may be present in the B1 or B21 horizons but rarely in the lower B subhorizons.

"The results of the random sampling in northeast Iowa...indicate that up to 60 percent of the better drained soils with mollic epipedons may contain grainy gray ped coatings in their subsoils. Based on estimates of 1.4 to 1.8 million acres [0.57 to 0.73 million ha] of well and moderately well drained Brunizem soils in the Cresco-Kasson-Clyde and Kenyon-Floyd-Clyde soil associations, it is inferred that similar ped coatings may occur in approximately one million acres [0.40 million ha] of Brunizem soils in northeast Iowa.

"In the Tama-Muscatine soil association approximately 75 percent of the soils in the eastern region and 35 percent of the soils in the western region may contain grainy gray ped coatings.... A projection of these estimates indicate that about 900,000 acres [360,000 ha] of such soils may occur in this soil association. Their common occurrence and strong expression in Cedar and Scott counties is evident."

Arnold and Riecken (1964, p. 359) hypothesize that these soils were forest soils that have become prairie soils "under prairie vegetation in the more recent course of their formation. Current concepts are that the surface layers (A1 to A3) of a typical Brunizem could form in about 300 to 500 years and that the A1-A2 horizon sequence of a Gray-Brown Podzolic soil can form in about the same number of years." In testing multiple hypotheses of soil formation, it was concluded that, for all possible sequences of soil formation, these soils had to be very young (Arnold, 1965).

Soil analysis of Buffalo Beats, a relict prairie in southeastern Ohio, shows that prairie and transition forest are developed on the same parent material — a lense of calcareous clay overlying shale. Invasion of this prairie by forest was determined to start ~ 300 years ago. The soil still under prairie remained well mixed — the A horizon having 0 percent more sand, +1 percent more silt, and -1 percent clay relative to the texture of the underlying C horizon (Wistendahl, 1975).

However, in less than 300 years time, the texture and the soil chemistry of the prairie soil under forest changed. The A horizon has 7 percent more sand, 5 percent more silt and 12 percent less clay relative to the underlying C horizon. Soil pH values under prairie are 6.6 in A, 7.2 in B, and 7.9 in C. Soil pH values under forest transition are 5.6 in A, 6.1 in B, and 8.0 in C (Wistendahl, 1975). Such a change in soil texture and pH indicates rapid expression of the downward eluviation/illuviation leaching process, which is natural given the soil water drainage of such a humid climate. That a tallgrass prairie ecosystem can stalemate the eluviation/illuviation leaching processes is testimony to the remarkably intense bioturbation and great biological activity occurring in its root zone.

The literature shows that chemical changes occur much more rapidly than morphological changes. Review shows that SOM under prairie soil with forest encroachment may change significantly on the order of 100 years. Soil properties, such as pH and exchangeable cations, will change even more rapidly (Birkeland, 1974, p. 204-205).

As indicated in Table 1, just the exclusion of fire from Illinois prairie results in marked and rapid decline in productivity. Therefore, loss of SOC is expected to be rapid and of the same order of magnitude time scale as decline in productivity.

With the removal of Native American stewardship, there also was a change in species composition; namely, the loss of legumes. Regarding Illinois prairie, as stated in the introduction of Betz and Lamp (1989), even detailed plant surveys of Illinois prairies in the 1910s and 1920s (e.g., Sampson,1921) were no longer representative of prairies encountered by the original settlers. Thus, the difference between presettlement and postsettlement prairie legume content is probably even greater than reported by Leach and Givnish (1996). Given that legume plant material is so N rich, and these prairie species tend to have such large and deep root systems, this significant decrease in legumes probably would have resulted in a significant and rapid (albeit yet to be quantified) decrease in SOC throughout the depth of even the geologically young (Wisconsin/Holocene) prairie soil profile.

Even in presettlement forest, removal of Native American presence is expected to have resulted in rapid and dramatic loss of SOC. For example, burning of open forest floor has been shown to increase legume content and soil N (a surrogate for SOM and SOC) by 50 percent in the upper 15 cm of forest soil in just 8 years of fire management (Garren, 1943; Niering and Dryer, 1989).

Krug and Winstanley (2000) concluded that the SOC content of Illinois' presettlement forest and prairie soils was appreciably higher (albeit yet to be quantified) than measured by 20th

Century soil scientists because of the absence of Native American land stewardship for more than a century.

Clearly:

"...leaving the area alone will not satisfactorily reestablish the original prairie because the large herbivores, bison, elk, and antelope formerly present are absent, and because fire would rarely occur naturally" (Hulbert, 1973, p. 15).

A recent study provides a rough look at what prairie-to-forest conversion may have done generally to prairie SOC:

"The invasion of woody vegetation into deserts, grasslands and savannas is generally thought to lead to an increase in the amount of carbon stored in those ecosystems. For this reason, shrub and forest expansion (for example, into grasslands) is also suggested to be a substantial, if uncertain, component of the terrestrial carbon sink. Here we investigate woody plant invasion along a precipitation gradient (200 to 1,100 mm [millimeters] yr^{-1}) by comparing carbon and nitrogen budgets and soil $\partial^{13}C$ profiles between six pairs of adjacent grasslands, in which one of each pair was invaded by woody species 30 to 100 years ago. We found a clear negative relationship between precipitation and changes in soil organic carbon and nitrogen content when grasslands were invaded by woody vegetation, with drier sites gaining, and wetter sites losing, soil organic carbon. Losses of soil organic carbon at the wetter sites were substantial enough to offset increases in plant biomass carbon, suggesting that current land-based assessments may overestimate carbon sinks" (Jackson et al., 2002, p. 623).

Earlier statistical analysis on 20,000 soil profiles suggested the moisture-SOC change relationship. Therefore, Jackson et al. (2002) looked at woody invasion of United States grasslands (one side of the fence allowed to revert to trees for 30 to 100 years) and changes in SOC and SON between 0 to 3 m soil depths across the above-mentioned 200 to 1100 mm yr^{-1} precipitation gradient. There were significant changes in SOC and SON down to 3 m soil depths. In 40 years at the wettest site, there was a loss of 44 percent of SOC and a 37 percent loss of SON (Jackson et al., 2002).

Shear and Stewart (1934) presented data which can provide insight into the effect of prairie to forest conversion on Illinois soil developed from Wisconsin-aged loess in east-central Illinois. Grassland soils are less acidic than forest soils, and different tree species have different abilities to acidify soil. Data show that white oak, the dominant tree of the early forests of Illinois, is an intense soil acidifier. Research at the University of Illinois' forestry plot in Urbana indicated that white oak acidified 0.9 m of prairie soil to pH 4.45 to 4.80 in just 56 years (Table 2).

In summary, soil-forming factors are responsible for the measured > 30-fold range in average SOC contents in the top 1 m of Illinois soil. If SOC contents were measured to the full depth of soil profiles ($\geq$ 3 m), the range would undoubtedly be even greater. Thus, well-informed manipulation of soil-forming factors is a potent means of enhancing SOC sequestration. With prairie and forest ecosystem change, ~50 percent change in SOC is possible on a decades-to-century time scale for the whole-soil profile. Assuming that preEuropean settlement SOC was 50 percent higher than postsettlement natural area forests and prairies, the plow layer of Illinois croplands is capable of sequestering ~1.7 billion metric tons CO_2-C, the top 1 m ~8.5 billion metric tons CO_2-C, and even greater amounts if the top 3 m of soil is considered. Given the dearth of SOC data for soil depths below 1.5 m, it is impossible to determine the true SOC sequestration potential for the whole-soil profile.

Table 2. Illinois Prairie Soil pH after 56 Years under Different Tree Species.

Soil depth (m)	*Silver maple*	*Green ash*	*Larch*	*White pine*	*White oak*
0.0-0.3	5.40	4.95	4.30	4.20	4.45
0.3-0.6	6.40	5.10	4.90	4.80	4.55
0.6-0.9	6.70	6.10	5.40	5.90	4.80
0.9-1.2	7.20	7.10	7.20	6.70	5.35
1.2-1.5	7.80	7.80	7.75	7.20	6.70
1.5-1.8	7.75	7.70	7.80	7.60	7.90

Source: Table 4 of Shear and Stewart (1934).

The literature shows that SOC can be sequestered in amounts exceeding natural presettlement SOC values for post-mature soils. This could be accomplished if human activities could be designed to achieve whole-soil profile nutrient enrichment and acid neutralization.

Response of Soil Organic Carbon to Agricultural Practices

Agricultural practices affected the interactive soil-forming factors that govern soil formation and SOC sequestration in Illinois. Native Americans were removed from the land prior to the waves of settlement that converted most of Illinois to cropland. Removal of Native American stewardship from the landscape was the first soil-forming factor changed, and resulted in an estimated SOC loss of > 8.5 billion metric tons CO_2-C prior to the breaking of ground by European settlers.

Removal of native plants and animals and their replacement with domesticated plants and animals are prominent examples of the change in the biological soil-forming factor. Tilling, draining, and fertilization changed the soil-forming factors of climate, parent material, topography (topographically-induced drainage and erosion), and time.

Agricultural practices had a profound impact on SOC sequestration because agricultural practices changed all of the soil-forming factors that govern SOC sequestration. Indeed, numerous studies cited above show that agricultural practices have resulted in the loss of SOC in the Midwest Corn Belt. On average, 40 percent SOC has been estimated to have been removed from the plow layer of both prairie and forest soils of the Midwest Corn Belt (Mann, 1985). The response of whole-soil SOC to agriculturally-related changes will now be examined from a soil genesis perspective.

This section first looks at the literature on how early and modern agricultural practices have induced SOC loss, and then at the literature on how agricultural management practices can be changed to increase SOC – sequester CO_2-C.

Soil Organic Carbon Loss Induced by Agriculturally-related Changes

Removal of Native American land-use practices from the landscape is a generally unrecognized avenue of SOC loss. While the two land-use systems had areas of overlap, the principal Old World agronomic land-use practice imposed on Illinois was the removal of natural ecosystems, and the manual plowing, weeding, and fertilization to maintain the introduced plants and animals of domesticated agroecosystems. The principal Native American land-use practice imposed on Illinois was to manipulate the plants and animals of the whole landscape. Today's Illinois ecosystem is obviously anthropogenic — mostly row crops. Illinois' presettlement landscape was also anthropogenic. But to most Old World eyes, the presettlement landscape looks wild, "natural" and untouched by human intervention (Wilhelm, 1991). Between the height of Native American land use and the time that the ground was broken by the plow, SOC was lost from the surface layer (0 - 20 cm) of natural areas. Estimates of cropland SOC loss from the surface layer do not recognize natural area SOC loss, therefore, surface-layer SOC losses are underestimated.

Furthermore, surface-layer SOC content of natural area prairie and forest soils were made in the 20th Century (Jenny, 1941; Mann, 1985). However, much of the agricultural development occurred nearly a century earlier when these natural areas would have had higher SOC contents. Also, estimates of SOC content were made under introduced, Old World vegetation. For example, even in Illinois' intensively studied, world-famous Morrow Plots, and at Missouri's prestigious Sanborn Field, soil N was not measured when the plots were first established. The Morrow Plots — the second oldest in the world — were established in 1876, and soil C and N were reported as being first determined in 1904. Unfortunately, the SOC content of the bluegrass fringe around the edge of the plots was assumed to be that of the original prairie soil (Odell et al., 1984a,b; Stevenson, 1986, p. 56). Sanborn Field was also established early, in 1888, and soil N values were determined in 1915. As with the Morrow Plots, so-called virgin conditions were estimated from Old World grass bordering the field (Woodruff, 1949). All of the above errors act in the same direction — all underestimate surface layer SOC.

That estimates of prairie and forest SOC content are low is supported by the historical record. Early agricultural accounts document Midwest prairie soils as having unprecedented fertility (even decades after land abandonment by Native Americans), apparently much greater than 20th Century prairie or the 20th Century grass lawns used as surrogates for presettlement prairie as the prairie soils were so rich in SOC and N that they could not grow wheat (e.g., Baily, 1856, p. 212; Welch, 1979, p. 10).

Corn, a Native American crop, is more tolerant of high N fertility than wheat, which is an Old World crop. Even so, corn suffered from the symptoms of excessive N (Snyder, 1905, p. 213) — even under methods of cultivation considered less than optimal during the early 1800s, "the corn grew 'from 12 to 15 feet [3.7 to 4.6 m] high on average' " (Buck, 1967, p. 133) with a single ear of corn growing from the top of each stalk (Buck, 1912, p. 147).

In the decades following the excess N supply problem years, Conner (1922) and others observed the supply of soil N from decomposition of SOM remained so high that fertilizer additions were not needed to sustain luxuriant crop growth (Smith, 1913). For example, prior to 1860, a traveler passing through Illinois noted:

"I saw fields of maize in which grain had been grown for 30 years and that, too, without any fertilizer. They left nothing to be desired for the stalks grow luxuriantly to the height of 15 feet [4.6 m]" (Sutton, 1976, p. 202).

Indeed, for some time the supply of soil N from decomposition of SOM appears to have exceeded the amount that could be taken up by the luxuriant growth of N-rich, highly productive crops. This is indicated by observations of free NO_3-N accumulations in Midwest Corn Belt soils of the late 1800s and early 1900s. Cropland soils contained so much free nitrate that accumulations of NO_3-N salt crusts on and near the surface during dry periods were not considered to be remarkable (e.g., King and Whitson, 1901; Scarseth et al., 1943).

Even in the decades after the early years of N transfer being so high as to exceed optimal crop yield, concentrations of NO_3-N in crops were all too often so high that NO_3-N poisoning of livestock was a widespread problem in the Corn Belt (Mayo, 1895; Davidson et al., 1941; Wright and Davidson, 1964; Deeb and Sloan, 1975). For example, during the 1800s, when drought killed corn plants in mid-season (preventing soil NO_3-N taken up by the plants from being converted to organic forms), the amounts of plant NO_3-N could be so great that plant stalks burned like fuses, e.g.,

"A casual examination of the samples of corn stalks received, revealed the presence of large quantities of nitrate of potash (saltpetre).... If a stalk was cut in two and tapped lightly upon a table, the crystals of potassium nitrate would be jarred loose and fall as a fine powder upon the table. Upon splitting a corn stalk, the crystals in the pith of the stalk could easily be seen with the unaided eye.... On lighting a bit of stalk with a match, it would deflagrate, burning rapidly like the fuse of a fire cracker. A chemical examination of a quantity of stalks gave 18.8 per cent of dry weight of the stalk nitrate of potash" (Mayo, 1895, p. 5).

In noting that the situation he analyzed was not unique, Mayo (1895) cited a previous example of the same thing analyzed by two other professors:

" 'In November, 1888, a Mr. Williams, near Grainfield, Gove county, this state, sustained a serious loss from a herd of 120 head of cattle.... The corn fodder of a portion of the field was so impregnated with the nitrate that many of the stalks would burn like a fuse, sometimes flashing into a blaze. On the outside of the stalks and just under the cuticle a white deposit of the nitre was visible on many stalks. An analysis of one stalk that may have been more than commonly charged with the salt, showed that one-fourth of the total weight of the stalk was saltpetre.... There was a large amount of organic nitrogen on and in the soil; there was sufficient moisture much of the time to permit nitrification and seldom so much moisture as to check it; the high temperature was favorable; there was not enough rainfall to leach the soil of the nitrate formed. So there was every opportunity for nitrate to accumulate in the soil, and from the soil to pass into the corn plants.... We have previously mentioned that in a portion of the field conditions favored the production of nitrate in the soil while lack of drainage prevented its loss in this way.' " (pp. 5-7).

Long-accepted estimates of SOC loss assume that losses of soil C and N are directly proportional (e.g., Albrecht, 1938; DeTurk, 1938; Jenny, 1941; Odell et al., 1984a,b; Stevenson, 1986), and estimates of soil N loss are used to estimate SOC loss where actual data are lacking, e.g.:

"Nitrogen, as the largest single item in plant growth, has been found to control crop-production levels, so that in the corn belt crop yields roughly parallel the content of organic matter in the soil.... With declining organic matter go declining corn yields and therefore lower earnings on the farmer's investment. Thus the stock of organic matter in the soil, particularly as measured by nitrogen, is a rough index of the land value when applied to soils under comparable conditions. According to studies in Missouri, for example, the lower the content of organic matter of upland soil the lower the average market value of the land" (Albrecht, 1938, p. 352).

Losses of SOC (and associated nutrients) were especially large after conversion of natural areas to cropland (Jenny, 1941):

"...with the removal of water through furrows, ditches, and tiles, and the aeration of the soil by cultivation, what pioneers did in effect was to fan the former simmering fires...into a blaze of bacterial oxidation and more complete combustion. The combustion of the accumulated organic matter began to take place at a rate far greater than its annual consumption. Along with the increased rate of destruction of the supply accumulated from the past, the removal of crops lessened the chance for annual additions. The age-old process was reversed and the supply of organic matter in the soil began to decrease instead of accumulating" (Albrecht, 1938, p. 348).

With each new disturbance of the plow layer, a flush of nutrients would be released to solution and to loss by erosion. The soil aging process was accelerated. As shown by long-term Morrow Plots' research on the effect of long-held, traditional farming practices, aging rate was different for different agronomic practices, resulting in varying losses of soil N (and presumably a directly proportional loss of SOC from the plow layer) which was greatest in the early years of cultivation. Rates of plow layer, N-inferred SOC-loss range from about 60 percent for unfertilized continuous corn, to 33 percent for unfertilized corn-oats-clover rotation, to 17 percent for fertilized corn-oats-clover rotation (Stevenson, 1986, p. 56). Initially high rates of SOC loss were credited to the rapid decomposition (mineralization) of labile SOM components, which resulted in initial high loss rates of CO_2 to the atmosphere, high rates of supply of plant nutrients, with initially high losses due to high harvest rates, high leaching rates, and initially high rates of volatile losses of N and S.

Superimposed on these biogeochemical SOC-loss mechanisms is the physical SOC-loss mechanism of erosion. Assuming equal rates of erosion over time, SOC and soil nutrient erosional losses were higher earlier simply because earlier eroded soil had higher SOC and nutrient content.

Estimated average loss of soil N from the plow layer of Corn Belt soils is about 40 percent:

"For soils of the corn belt, about 25 percent of the N was found to be lost the first 20 years, 10 percent the second 20 years, and 7 percent the third 20 years" (Stevenson, 1986, p. 55).

Through comparison of cultivated and uncultivated soils, estimated average loss was 40 percent soil C from the plow layer of alfisols (forest soils) and mollisols (prairie soils) in the central United States (Mann, 1985). As discussed earlier in this section, estimates of SOC loss are low because they underestimate the natural SOC content of the plow layer.

Estimates of Subsoil SOC

Estimates of SOC loss are also low because they do not consider SOC loss from below the plow layer. As with plow-layer-SOC losses, subsoil-SOC losses result from both the suspension of Native American land-use practices and initiation of cropping practices.

Native American land-use practices promoted SOC sequestration to $\geq$ 3 m soil depth, and their removal would have resulted in loss of subsoil-SOC. Field experiments show this deep SOC in prairie soils is labile and decreases with removal of the prairie ecosystem (Jackson et al., 2002). These empirical observations are supported by mechanistic study:

"Although bulk C concentrations and ^{14}C contents of SOM at > 1-m depths are low, estimates of turnover from fine-root inputs, CO_2 production, and the ^{14}C content of CO_2 produced at depth show that up to 15 % of the carbon inventory in the deep soil has turnover times of decades or less. In these soils, the amount of fast-cycling soil carbon between 1- and 8-m depths (2 to 3 kg C m^{-2}, out of 17 to 18 kg C m^{-2}) is significant compared with the amount present in the upper meter of soil (3 to 4 kg C m^{-2} out of 17 to 18 kg C m^{-2})" (Trumbore, 1997, p. 8288).

Also, subsoil-SOC losses would have been induced upon initiation of agronomic cropping practices. The most obvious loss of subsoil SOC is from draining wet, high-SOC soils by tile drains and ditches to 1 to 1.5 m depth for optimum crop production (Alexander, 1905; King, 1918; Van Vlack and Norton, 1944; Hewes, 1951; Pavelis, 1987; Goolsby et al., 1999; Mitsch et al., 1999): "Without drainage, it is hard to imagine the U.S. Midwest as it has developed to be the most productive agricultural area anywhere in the world" (Fausey, 1993, p. 519).

It has been long known that drainage, in and of itself, results in the oxidation of vast amounts of previously waterlogged subsurface SOC (e.g., Albrecht, 1938; Mitsch et al., 1999, pp. 4-6). Nevertheless, estimates of subsoil SOC lost due to draining reportedly have yet to be made (e.g., Goolsby et al., 1999). Such SOC loss is apparently huge. As previously mentioned, the quantity of average soil N values in the top 1 m has been measured to range from about 6,700 kg ha^{-1} in excessively drained upland soils to 224,500 kg ha^{-1} in wetland Illinois soil (Hopkins, 1910).

Assuming C:N ranges from 10 to 12, SOC ranges from ~70 metric tons ha^{-1} to ~2,500 metric tons ha^{-1}. In Illinois, 4.05 million ha of 9.31 million ha of cropland has been drained (Zucker and Brown, 1998, p. 7). The range in SOC is slightly greater as C:N ratios are somewhat larger in organic-rich wetland soils than in upland soils, and the depth and SOC content of wetland soils are greater (Hopkins, 1910; Stevenson, 1986). Assuming that the drained Illinois soils had 500 to 1,000 metric tons SOC ha^{-1} in the top 1 m, and that 40 percent of this SOC was lost with draining, this represents a loss of 200 to 400 metric tons SOC ha^{-1}. Subtracting the state average — an estimated 123.5 metric tons SOC ha^{-1} lost from the topsoil — drainage enhanced SOC loss ranges from 76.5 to 276.5 metric tons SOC ha^{-1} from the 4.05 million ha of drained Illinois croplands. Estimated SOC loss from Illinois cropland drainage increases the original estimate from > 1.15 billion metric tons to a range > 1.46 to > 2.27 billion metric tons. Including the corrected estimate of topsoil-SOC loss increases estimated SOC loss to a range > 2.0 to > 2.9 billion metric tons. Therefore, > 2.0 to > 2.9 billion metric tons CO_2-C may be sequestered in the top 1 m of Illinois soils if Illinois cropland soils were returned to their revised estimated SOC values that existed when Native Americans inhabited the land. This range in estimated SOC values does not include estimates of > 1 m subsoil-SOC loss upon cropland draining or subsoil-SOC loss from undrained Illinois cropland.

Estimates of subsoil-SOC lost due to cropping and harvesting have yet to be made. Classic studies, such as those conducted by Jenny (1941) and at the Morrow Plots (e.g., DeTurk, 1938; Odell et al., 1984a, b), focused their conclusions about the effects of management practices based on soil depths of 15 to 30 cm in spite of the fact that crop roots affect the subsoil. For example, Weaver et al. (1922) and Crist and Weaver (1924) observed that the roots of grain crops penetrated most deeply into soil during the critical periods of blossoming and the filling of the grain, deriving their moisture and nutrients largely from these deep roots:

"The fact that roots absorb nutrients at deep levels in the subsoil as well as from the surface layer should be given greater attention by all plant growers. The current idea that it is mainly the surface layer of soil that supplies the plant with nutrients and that the subsoil is the crop's reservoir for water, should give way to the fact that it is the whole soil mass pervaded by roots that determines root activities" (Crist and Weaver, 1924, pp. 145-146).

Perusal of the scientific agronomic literature to the present shows that this problem has not corrected itself. Indeed, with the advent of low- and no-till agriculture, surface SOC studies have become a cornerstone of agronomic research.

Effects of Low- and No-till Agriculture on SOC Content

Intuitively, low- and no-till agricultural practices may appear to be remedies for increasing SOC over other tillage practices (West and Post, 2002). However, scientifically-critical reviews show that increased oxidative loss of SOC induced by tilling (Kristensen et al., 2000) may be offset (or even overshadowed), if sufficient surficial plant material is incorporated into the soil by tillage. The decades-long increase in crop yields coincides with the decades-long increase in subsurface and surface crop residues available for incorporation into soil and SOC buildup by conventional cultural practices (e.g., Garman, 1970; Larson et al., 1972.; Odell et al., 1984b; Li et al., 1994).

Extensive reviews show that the results of tillage practice are ambivalent and depend upon many interactive factors not yet fully understood. No-till agriculture "generally leads to an increase of C in the top 5 to 10 cm of the profile, relative to the plowed soils (Kern and Johnson, 1993; West and Post, 2002). Within the entire plow layer, however, organic C content under no-tillage may be higher (Kern and Johnson, 1993) or lower (Karlen et al., 1991) than under plow tillage" (Alvarez et al., 1998, p. 138).

Wander et al. (1998, p. 1704) observed that, "Most studies of the influence of conservation tillage on SOM emphasize accumulation in surface soil depths (Blevins et al., 1977; Doran, 1987; Halvin et al., 1990; Carter, 1992). This has led to the assumption that the use of conservation practices will lead to net accumulation of SOM. Increased SOM storage is not always observed in soils under conservation tillage management, particularly when the C content of deeper soil depths is considered (Angers et al., 1993, 1995, 1997; O'Hallaran, 1993) or when comparisons are made on a mass basis (Carter and Rennie, 1982; Powlson and Jenkinson, 1981; Ellert and Bettany, 1995)."

Indeed, a 10-year study of three, fine-textured, poorly drained soils in Illinois found that the effect of no-till versus conventional till on soil at depths between 0 and 30 cm generally increased C and N in the top 5 cm of soil at the expense of soil C and N lower in the profile. No-till increased total soil C and N in only one of the three Illinois soils relative to conventional tillage (Wander et al., 1998).

Continuous monitoring of CO_2, conducted by the PI in a no-till field on a heavy Illinois soil showed a net gain of C to the ecosystem when soybean fallow was followed by corn, and a net loss of C when corn fallow was followed by soybeans. In four years of monitoring (two corn and two soybean crops), there was a net loss of C from the ecosystem (unpublished results).

Although claims based on 2.5 cm, 5 cm, 10 cm, 15 cm, 20 cm, and 30 cm soil depths are being asserted as showing that low- and no-till agriculture sequester SOC (e.g., Blevins et al., 1977; Doran, 1987; Liebhardt et al., 1989; Halvin et al., 1990; Wood et al., 1991; Carter, 1992; Kern and Johnson, 1993; Lal et al., 1994; Soon, 1994; Matson et al., 1997; Drinkwater et al., 1998; Tilman, 1998; Kristensen et al., 2000; Izaurralbe et al., 2001; Ortega et al., 2002; West and Post, 2002), science has continued to accumulate knowledge that many (if not most) of the nutrients harvested in grains and vegetables — and exported from the field — come from the subsoil below the plow layer (e.g., Weaver et al., 1922; Crist and Weaver, 1924; Miller, 1938, pp. 145-148; Murdock and Engelbert, 1958; Hanway and Thompson, 1967; Gass et al., 1971; deMooy et al., 1973; Mengel and Scherer, 1981; Mengel et al., 1987; Kuhlmann, 1990; Li et al., 1990; Kuhlmann and Baumgartel, 1991). At the time of flowering and grain fill crops derive most of their nutrients and water from the subsoil (Mengel and Barber, 1974; Arya et al., 1975a, b; Emery, 1975; Levan et al., 1987).

Subsoil SOC and Nutrient Losses

Subsoils supply Corn Belt crops with nutrients from considerable depth. In Illinois average corn root depth was determined to be 1.8 m (Boone et al., 1978, p. 32), wheat 1.2 m (Majchrzak et al., 2001), and soybeans 0.9 to 1.4 m (Fehrenbacher et al., 1969), 1.2 to 1.6 m for soybeans under drought stress (Emery, 1975). Whereas Corn Belt soils are said to have lost 40 percent of their nutrient-bearing SOC in the upper soil profile roughly corresponding to the plow layer, Kucharik et al. (2001) estimate 63 percent loss of SOC from the top 1 m of soil between 1860 and 1950.

The very nature of the soils and crops of the Corn Belt makes these soils subject to subsoil SOC depletion because the harvest is especially dependent upon subsoil SOC. Indeed, crop harvest dependence on subsoil SOC is one of the reasons why the Corn Belt is our nation's breadbasket:

"It is of more than passing interest that the cereal crops, namely: corn, spring and winter wheat, oats, barley, sorghum, and millet, have their center of greatest production in that portion of the United States originally covered by grassland... and other crops, like alfalfa and flax, which are similar in growth habits to wild legumes... growing among the grasses, also have their greatest acreage in grassland. Likewise, the largest area of fruit production... and bush fruits ...are in those portions of the United States formerly occupied by native species of similar habits, i.e., forest trees and shrubs" (Weaver, 1927, p. 1).

"In the subclimax [Prairie Peninsula] and other tall-grass prairie the presence of a continuous cover of tall, deeply rooted grasses indicates conditions favorable for the production of cultivated plants of similar habit, a fact fully substantiated by the excellent yields of wheat, oats, and corn.... The deeply rooted [prairie] species have favorably modified the subsoil to great depths, enriching it with nitrogen, adding humus by root decay, as well as making it more porous, and as a result of absorption, vast stores of nutrients have been obtained from deeper soils and upon the death of the tops deposited in the surface soil. Thus the tall-grass prairie furnishes the most productive region for agriculture" (Weaver, 1927, pp. 6-7).

"Maize... thrives best and produces the greatest yields in that part of the grassland with the greatest rainfall. In terms of native grasses this means a deep, moist soil, a luxuriant growth, throughout the entire growing season, of tall, coarse vegetation which furnishes abundant organic material that decays without too rapid oxidation and maintains the productivity and tilth of the soil. Corn is a tall, luxuriant, coarsely rooted cereal [Figure 4] which finds its greatest production on land formerly occupied by grasses of somewhat similar ecological requirements..." (Weaver, 1927, p. 10).

Corn Belt soils also are susceptible to SOC depletion because the higher effective wetness of the subclimax prairie (the Prairie Peninsula east of the lime-line) results in higher SOM content. And, increased effective wetness results in increased soil microbial activity (Zak et al., 1994) which increases the mineralization (decomposition or turnover rate) of SOM.

A hallmark of soil genesis under tallgrass prairie is the distribution of great amounts of SOM, associated plant-available nutrients, and weathering to 3 m, or more, into the soil (Willman et al., 1966; Weaver 1954; 1958a,b; Soil Conservation Service, 1968; Harlan et al., 1977; Lerner, 1980; Risser et al., 1981; Tandarich et al., 1994; Dreher et al., 2002; Prairie Frontier, 2002). Of the SOM that exists down to a depth of 1.5 m, slightly less than 20 percent is in the plow layer and slightly more than 80 percent between the plow layer and 1.5 m. Analysis shows that there is as much SOM in the 1 to 1.5 m layer as in the plow layer (Hopkins, 1910; Marbut, 1929; Schreiner

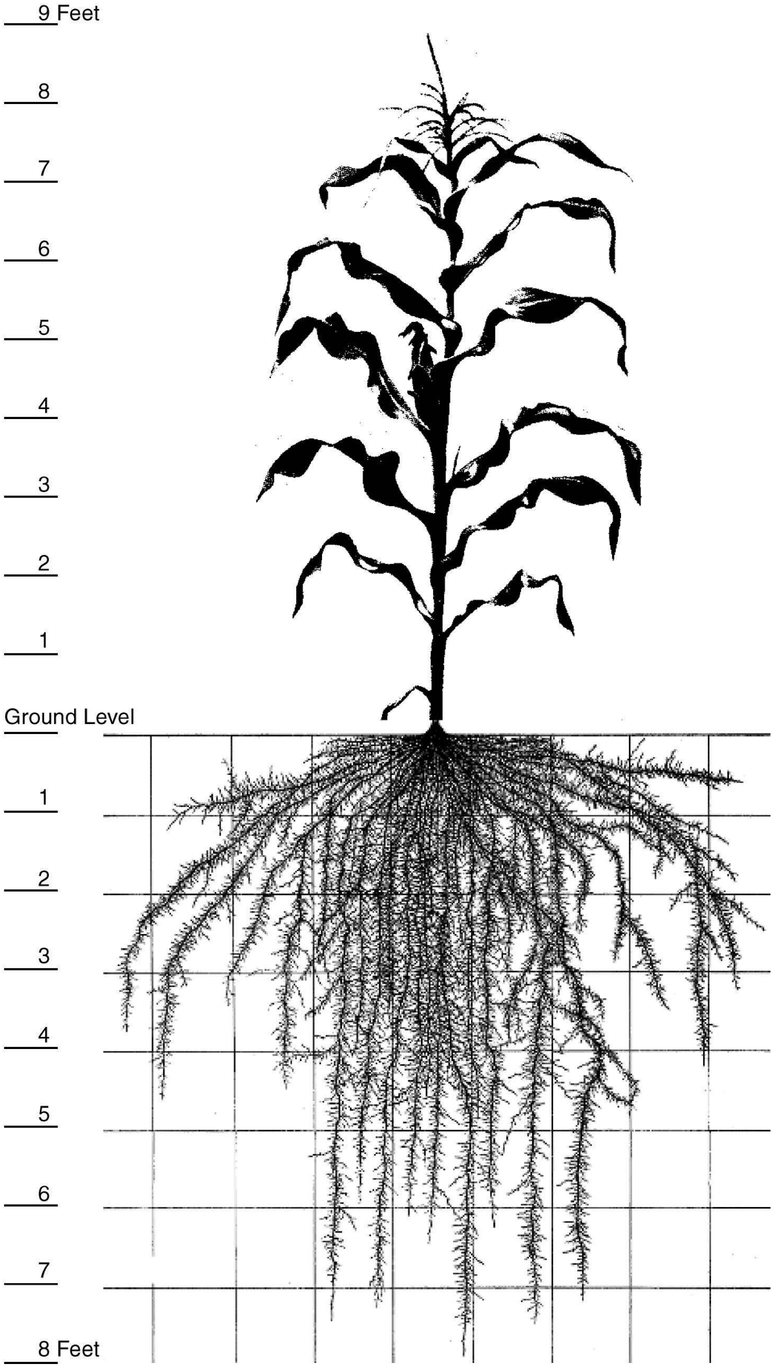

Figure 4. Whole-plant profile of corn.

and Brown, 1938; Krug and Winstanley, 2002). Because 80 percent of the SOM is in the 0.2 to 1.5 m layer it is important to understand subsoil SOC changes due to tillage and production management practices. Subsoil SOC loss necessarily occurred with the switch from native prairie plant species to the common introduced crop species of today. Native prairie plants put most of their productivity (organic matter and associated nutrients) and humus-forming biomass belowground. However, major Corn Belt crops — corn, soybeans, and wheat — put two to three times more of their organic matter and associated nutrients aboveground than belowground (e.g., Bartholomew and McDonald, 1966; Hanway and Weber, 1971; Mayaki et al., 1976). Overall, the literature shows that prairie ecosystems put down ~10 times more root biomass than do Corn Belt agroecosystems (Weaver 1954; 1958b; Bartholomew and McDonald, 1966; Hanway and Weber, 1971; Mayaki et al., 1976; Risser et al., 1981; Reeder et al., 2001, p. 142; Slobodian et al., 2002). Whereas prairie ecosystems put most of their C and nutrients belowground, Corn Belt agroecosystems put most of their potential humus-forming C and nutrients aboveground, which are harvested and removed from Corn Belt agroecosystems (Goolsby et al., 1999).

The importance of subsoil SOC was recognized early by Weaver et al. (1922) and Crist and Weaver (1924), who also recognized the importance of subsoil fertility. Additionally, Hopkins — Chief of Agronomy and Chemistry of the Illinois Agricultural Experiment Station and President of the U.S. Association of Official Agricultural Chemists — recognized the importance of subsoil fertility (1910). For example:

"Even a rich subsoil has little or no value if it lies beneath a worn-out surface, for the weak, shallow-rooted plants will be unable to reach the supply of plant food in the subsoil. If, however, the fertility of the surface soil is maintained at a high point, then the plants, with a vigorous start from the rich surface soil, can draw upon the subsurface and subsoil for a greater supply of plant food.

"By easy computation it will be found that the most common upland soil of Champaign county, the brown silt loam prairie, does not contain more than enough nitrogen in the plowed soil for the production of maximum crops for nine rotations (36 years)" (Hopkins et al., 1918, pp. 7-8).

In the Chapter, "Formation of Soil" in *Soils and Men. Yearbook of Agriculture 1938*, the USDA recognized that subsoils are naturally an important source of plant nutrients:

"Two of the chief functions of plant and animal life, so far as soil profile development is concerned, are the furnishing of organic matter for the soil and the bringing in of plant nutrients from the lower layers to the upper ones" (Byers et al., 1938, p. 963).

Early research on the relationship between uptake of subsoil nutrients on crop yields concluded:

"... Absorption of nutrients at levels below the surface foot affects materially the quantity and quality of the yield. It does not lose its additive effect even when the surface foot is abundantly supplied with a similar nutrient. Thus the chemical composition of the subsoil and the soil solution is very important.

"... Time of absorption is an important factor. The effects of the nutritive salts are most marked on both the quantity and quality of yield early and late in the development of the plant, that is, when absorption is confined largely to the first foot of soil and the crop is tillering, and again when the younger portions of the longer roots are absorbing from the deeper levels at the time of heading. Thus an ample distribution of the deeper portion of root system in a rich subsoil solution at the later critical period of growth is exceedingly important. Consequently, a knowledge of the development and extent of the roots of crop plants is of primary interest.

"... These experiments show the importance of the subsoil as a source of nutrients for crops, and the effects upon plant development. They emphasize the values to be gained by fertilizer practices which take the composition of the subsoil into account" (Crist and Weaver, 1924, p. 147).

Whereas crop fertilizer recommendations are based on regular analyses of available nutrients in the surface soil, at mid-20th Century, scientists still recognized that crops use nutrients from the whole depth of their rooting zones. In order to update and revise their fertilizer recommendations, in 1967-1969, the University of Illinois at Urbana-Champaign analyzed plant-available P and K in the 0 to 15 cm surface soil, 30 to 46 cm subsurface soil, and 61 to 76 cm subsoil of cultivated soils throughout the state. Median quantities of plant-available P were reported by Peck (1968) to be 35 to 45, 7 to 11, and 7 to 11 kg ha^{-1} for the three respective soil layers. Median quantities of plant-available K were reported to be 303 to 336, 236 to 269, and 270 to 302 kg ha^{-1} for the three respective soil layers. Based on these data, depth of crop rooting in various soils, timing, and amount of plant nutrient requirements and contents, the state was divided into zones for P and K fertilizer recommendations (Aldrich et al., 1971).

And so, regarding crop utilization of the subsoil, the *Illinois Agronomy Handbook* recognizes that subsoils are important for the P, K, and S nutrition of plants:

"Illinois has been divided into three regions in terms of the inherent phosphorus-supplying power of the soil below the plow layer in dominant soil types" (Hoeft and Peck, 2000, p. 109).

The importance of subsoil P nutrition is illustrated by a radioisotope P study conducted on corn growing on Wisconsin Corn Belt soils. Of the isotopic P taken up by corn from the 0 to 76 cm soil layer, 57 to 80 percent came from subsoils (> 15 cm), an average of 68.5 percent (Table 3).

Regarding S:

"Organic matter is the primary source of sulfur in soils, so soils low in organic matter are more likely to be deficient than soils high in organic matter" (Hoeft and Peck, 2000, p. 120). It is recognized, in principle, that sulfur is essential for building SOM:

"Early season sulfur [deficiency] symptoms may disappear as rainfall contributes some sulfur and as root systems develop to exploit greater soil volume" (Hoeft and Peck, 2000, p. 119).

Regarding crop K nutrition derived from below the plow layer, the *Illinois Agronomy Handbook* states:

"Silt-loam soils in the 'low' [potassium] area in southern Illinois (claypans) are relatively older in terms of soil development; consequently, much more of the potassium has been leached out of the rooting zone. Furthermore, wetness and a platy structure between the surface and subsoil may interfere with rooting..." (Hoeft and Peck, 2000, p. 111).

As noted above, it was recognized early in Illinois' history of scientific agriculture that crop roots grow down into the subsoil where SOM could be mineralized by the rhizosphere for the plant to acquire subsoil nutrients (e.g., Hopkins, 1910; Hopkins et al., 1918):

"Organic matter may well be considered as fuel for bacterial fires in the soil, which operates as a factory producing plant nutrients.

"Decomposition by micro-organisms within the soil is the reverse of the process represented by plant growth.... Growing plants, using the energy of the sun, synthesize carbon, nitrogen, and all other elements into complex compounds. The energy stored up in these compounds is then used more or less completely by the micro-organisms whose activity within the soil makes nutrients available for a new generation of plants. Organic matter thus supplies the 'life of the soil' in the strictest sense" (Albrecht, 1938, p. 348).

Table 4 illustrates the release of mineral N from the decomposition of SOM in bulk soil (root-free soil) between 0 to 120 cm soil depth from fields that have been cultivated for 25 years with and without fertilization. Mineralization rates are greater than indicated by rates determined from bulk soils, (Table 4), because roots are not passive systems that rely only on bulk-soil microbiology for nutrients. Roots are active systems that aggressively promote near-root

Table 3. Percentage of Phosphorus Obtained by Corn at Different Depths in Various Soils.

Soil Depth (cm)	*Miami silt-loam*	*Dodge silt-loam*	*Parr silt-loam*	*Kewaunee silty-clay loam*
0-15	36.4	43.1	27.0	19.4
15-30	45.9	33.3	23.7	41.8
30-46	6.0	11.7	12.1	21.8
46-61	5.1	8.4	6.5	17.0
61-76	6.6	3.5	30.8	—

Source: Murdock and Engelbert (1958).

Table 4. Nitrogen Mineralization Amounts from Soil Organic Matter by Depth over an 11-week Period.

Soil depth	*Fertilized plot*		*Unfertilized plot*	
(cm)	*(kg N ha^{-1})*	*(Percent of total)*	*(kg N ha^{-1})*	*(Percent of total)*
0-20	55	40	16	21
20-40	30	22	13	16
40-60	18	13	14	18
60-120	35	25	35	45

Source: Table 5 of Hadas et al. (1989).

ecosystems (rhizosphere) to enhance plant nutrient acquisition. This is done, in part, by accelerating decomposition (mineralization) of SOC (Barley, 1970; Goss, 1991; Killham, 1994; Qian et al., 1997; Hinsinger, 1998):

"In the first place, the number of roots found in any given area of soil is no indication of their activity. It is a common observation that the first roots formed in the upper portion of the soil become suberized or cutinized so that they are totally incapable of absorbing, even if that portion of the soil is moist" (Miller, 1938, p. 146).

Research continues to support this long-held view, e.g.,

"Roots of grain crops may penetrate to depths of 2 m or more.... The small proportion of roots found at these depths, however, can be responsible for a major portion of root activity for nutrient uptake in later growth stages with unfavorable conditions above of dried soil and depleted nutrient supply..." (Hanway and Olson, 1980, p. 684).

Given the root depths achieved by major crops in Illinois (Fehrenbacher et al, 1969; Emery, 1975; Boone et al., 1978, p. 32; Majchrzak et al., 2001), and the climatic and soil characteristics of the Illinois Corn Belt, it is evident that subsoil nutrients were, and are, an important component of the nutrients harvested and exported from the field. Corn Belt crops benefit greatly from the deep, humus-rich soils from which crop rhizospheres extract a rich store of nutrients.

Nevertheless, agronomic research traditionally has concentrated on SOC and nutrients in the plow layer. For example, an early study at the Morrow Plots at the University of Illinois at Urbana-Champaign indicated a loss of about 20 percent of soil N in the plow layer after just 16 years of growing corn. Studies in Illinois, Indiana, and Wisconsin for a variety of crops indicated a loss of about one-third of soil P after about 50 years (Hopkins, 1910, pp. 559-560). A century of mining the soil of its nutrients (e.g., N, P, K, S, Ca, Mg) caused natural soil fertility and crop yields to decline to the point that even greater additions of nutrients became necessary (e.g., Conner, 1922; Albrecht, 1938; DeTurk, 1938; Whiteside and Smith, 1941; Viets and Hageman, 1971; Odell et al., 1984a,b; Stevenson, 1986), which — along with improved plant varieties and agronomic practices — improved yields (Viets and Hageman, 1971; Stevenson, 1986, 1994; Avery, 1991; Zimdahl, 1999).

However, along with fertilization and greater crop harvests came greater export of humus-building nutrients, N, P, and S (Schoenau and Bettany, 1987; Stevenson, 1994) and, thereby, elevated rates of SOC loss. That fertilization and greater crop harvests are resulting in soil depletion runs contrary to today's view that increasing harvests are being obtained while maintaining or increasing SOC. This view comes from looking at the surficial soil and assuming that this 2.5 cm to 30 cm slice of soil represents the whole ≥ 3 m depth of the Corn Belt soil profile (e.g., Blevins et al., 1977; Doran, 1980, 1987; Liebhardt et al., 1989; Halvin et al., 1990; Wood et al., 1991; Carter, 1992; Kern and Johnson, 1993; Lal et al., 1994; Matson et al., 1997; Alvarez et al., 1998; Drinkwater et al., 1998; Tilman, 1998; Wander et al., 1998; Kristensen et al., 2000; Robertson et al., 2000; Bergstrom et al., 2001 Izaurralbe et al., 2001; Ortega et al., 2002).

That crop fertilization could enhance SOC and nutrient mining of the subsoil was indicated in the broader scientific agricultural literature of a century ago:

"Frank (1893) grew corn and peas in such a manner that half of the roots of each plant grew in separate vessels. Each vessel contained the same amount of sand and was watered with the same nutrient solution, with the exception that to one vessel a portion of calcium nitrate was added, while the other received no nitrogen compounds. In the vessel containing the nitrogen-free medium, only a few small branch roots were formed, while the vessel containing the nitrogen compound was filled with a thrifty root growth. This same effect of nitrogen compounds on the secondary root formation of vetch, clover, corns, beans, and alfalfa was observed by Muller-Thurgau (1894)."

"Von Seelhorst (1902) carried on experiments to determine whether or not the use of fertilizers affected the number of roots of spring wheat, rye, peas, flax, beans, potatoes, beets, and barley. These plants were grown separately on two series of plots. One of the series had been fertilized annually for 25 years with fertilizers containing nitrogen, phosphorus, and potassium, although the amounts stated are not given, while the other series received no fertilizers during that period. The following table is a summary of the average number of roots found in an area of 314 sq. cm. at the various depths stated:

"

	Number of roots at a depth in soil Centimeters of				
	25	50	75	100	125
Fertilized..	500	307	197	109	52
Unfertilized..	459	206	158	92	43

"

(Miller, 1938, p. 127).

The presence of more roots in the deeper layers of the fertilized soil compared to the unfertilized results in more nutrients being removed from the fertilized soil's deeper layers. It is still recognized in today's scientific agronomic literature that surface fertilization may enhance mining of nutrients from subsoils:

"The value of a green manure crop in enriching the topsoil with nutrients from the subsoil is determined by its total nutrient uptake, the percentage derived from the subsoil and its ability to take up... [nutrients]... not available to the cash crop" (Witter and Johansson, 2001, p. 139).

Using rubidum (Rb) as an analog for K, and based on relative uptake from three different soil layers — 10 to 20, 50 to 60, and 80 to 90 cm — studies of green manure crops and a cash barley crop showed that these plants derived 41 to 67 percent of their K from the subsoil (Witter and Johansson, 2001).

An experiment by Kuhlmann (1990) on loessal soils demonstrated the relationship between crop root depth (at > 0.05 cm cm^{-3} root density) and percent nutrient uptake from the subsoil with topsoil — 0 to 30 cm — having 9 mg K 100 g^{-1} soil and subsoil having 16 mg K 100 g^{-1} soil. At harvest, lettuce with a rooting depth of 40 cm, had 20 percent of its K come from the subsoil. Peas, with a rooting depth of 50 cm, had 30 percent of its K come from the subsoil. Spinach, with a rooting depth of 60 cm, had 44 percent of its K come from the subsoil. Spring wheat, with of rooting depth of > 90 cm, had about 60 percent of its K come from the subsoil.

Using spring wheat:

"In subsoils with similar K contents, uptake from the subsoil decreased significantly from 65 to 21 % of total K uptake, as K contents in the topsoils [0 to 30 cm] increased from 4 to 8 mg K/100g.

"On sites with the same contents in topsoils (9 mg K/100g), the subsoil supplied 12 to 61 % of total K uptake as the K contents of the subsoil increased from 2 to 27 mg K/100g.

"The contribution of uptake of K from the subsoil increased with development of the crop, from 8 % at first node stage to 35 % at ear emergence, as the proportion of total root length in the subsoil increased.

"High root densities in the topsoil (9 cm/cm^3) resulted in competition for K between roots and increased uptake of K from the subsoil" (Kuhlmann, 1990, p. 129).

Regarding utilization of subsoil N, ^{15}N was placed at depths of 9, 60, 120, and 180 cm in a cornfield — planted on Sharpsburg silty clay loam, a mollisol developed in loess deposited on alluvium — in eastern Nebraska. The experiment was to determine depth from which corn derives N, the distribution of this N (^{15}N) between grain and stover, and the effect of rate of N fertilization on corn N uptake:

"The largest amount of [^{15}N] was found in the stover of those plants growing on plots in which the tracer was placed at a depth of 9 cm. This suggests that much of the N taken up during the vegetative growth stage remains there, while N taken up later is channelized directly into the grain. The isotope contents of the grain... clearly show that growing on plots containing the lowest and middle amounts of residual N [85 kg N ha^{-1} yr^{-1} and 165 kg N ha^{-1} yr^{-1}] extracted considerable tracer from depths of 60-120 cm. The high levels of residual N in plots treated successively with 250 kg N/ha apparently decreased N absorption from the lower portions of the soil profile" (Gass et al., 1971, pp. 292-293; Table 5).

The effects of crop management practices on crop yield, plow layer and subsoil nutrient contents were researched in Illinois. For long-term corn-legume crop rotation on a fertilized and unfertilized Corn Belt prairie soil developed on loess (Cisne silt loam):

"On the untreated Cisne soil [corn-legume rotation with cornstalks and legumes turned under (R)] the fertility level in the A_1 and A_2 horizons was obviously so low that corn roots were unable to develop with sufficient vigor to penetrate the subsoil very extensively.... Where soil treatment [R, lime, rock phosphate, and K_2SO_4]...was applied, the roots penetrated the claypan and were extensively developed in it.... Moisture determination at the time of sampling indicated that the corn roots had used moisture from the B and D_1 horizons.... It is also probable that there was some nutrient uptake from the claypan.... On Cisne, where sufficient amounts of plant nutrients were added and legumes turned under, corn roots were highly developed throughout the compact, slowly permeable claypan" (Fehrenbacher and Snider, 1954, p. 290).

Table 5. Uptake of N^{15} by Corn from Different Soil Depths Compared to Previous Annual Rates of Nitrogen Fertilization.

Previous nitrogen fertilization rate ($kg\ ha^{-1}\ yr^{-1}$)	*Depth of N^{15} placement (cm)*	*Relative proportion of N^{15} absorbed from various depths (%)*
85	9	32
	60	28
	120	29
	180	11
165	9	30
	60	36
	120	32
	180	2
250	9	59
	60	33
	120	7
	180	1

Source: Gass et al. (1971).

Fehrenbacher and Snider (1954) examined soil profiles to a depth of ~1.8 m (Table 6) which allowed observation of subsoil nutrient/plant interactions. Looking at crop and soil data in the normal fashion — crop yield, stover production, and soil fertility in the plow layer — leads one to conclude fertilization practice was a great success. Not only was corn yield raised from 20 to 75 bushels per acre, but the soil had also been built up. Soil P, K, and Ca was increased by fertilizer additions and soil N by soil incorporation of legume biomass, all of which would result in soil carbon sequestration — in spite of increased removal of these nutrients and export of C in harvested grain (Table 6).

The Cisne subsoil tells a different story, however. Fertilization caused an even greater depletion of nutrients than nonfertilization. Examining 30 cm depth increments, fertilization resulted in enhanced depletion of N, K, and Ca below 30 cm, and enhanced P depletion below 90 cm relative to depletion from crop growth and harvest from unfertilized soil. Whereas fertilization enhanced the amount of root mass left in Cisne subsoil (> 30 cm soil depth) by ~500 percent — 113 kg root ha^{-1} in unfertilized soil and 531 kg root ha^{-1} in fertilized soil — and thereby increased the amounts of plant nutrients left by the roots in the subsoil, the net effect was to deplete even more nutrients from the subsoil (Table 6a). Using N as a surrogate for SOC, and assuming a C:N ratio of 10, legume rotation and fertilization resulted in a N-inferred loss of 17,380 kg SOC ha^{-1} for soil depths between 30 and 107 cm.

Whereas an N-inferred increase of 22,660 kg SOC ha^{-1} is indicated for the top 30 cm of soil (Table 6a), loss of subsoil SOC is more substantial because the lost subsoil SOC was more aged, and more permanent than SOC gained in the topsoil.

The net effect of this legume rotation fertilization experiment was to accelerate the aging of this Illinois prairie soil, not rejuvenate it.

Table 6a. Soil and Crop Properties of Fertilized and Unfertilized Cisne Silt Loam.*

Soil horizon	*Depth (cm)*	*Root ($kg\ ha^{-1}$)*	*Root (% of total)*	*pH*	*Total N ($kg\ ha^{-1}$)*	*Available P ($kg\ ha^{-1}$)*	*Available K ($kg\ ha^{-1}$)*	*Available Ca ($kg\ ha^{-1}$)*
Ap	0-18 / 0-23	1,939 / 679	65.5 / 81.7	5.9 / 4.7	3,222 / 2,685	157 / 34	246 / 145	3,748 / 1,533
A21	18-28 / 23-36	368 / 72	12.4 / 8.6	5.6 / 4.9	2,372 / 1,566	45 / 34	13 / 157	2,585 / 1,578
A22	28-41 / 36-46	128 / 16	4.3 / 1.9	5.1 / 5.2	1,298 / 1,298	34 / 9	179 / 190	1,622 / 1,354
B2	41-79 / 46-76	239 / 41	8.0 / 5.0	5.2 / 5.4	1,343 / 1,343	34 / 16	235 / 224	4,655 / 4,498
B3	79-104 / 76-94	176 / 19	6.0 / 2.3	6.9 / 6.5	918 / 895	67 / 22	35 / 224	5,013 / 4,789
D1	104-147 / 94-107	112 / 4	3.8 / 0.5	7.0 / 7.0	806 / 895	134 / 101	224 / 235	4,878 / 4,655
D2	147-183 / 107-183	Trace / Trace	— / —	— / —	— / —	— / —	— / —	— / —
		2,962 / 831	100.0 / 100.0					
	0- 30 **	2,327 / 718	78.6 / 86.4		5,794 / 3,528	207 / 50	487 / 230	6,583 / 2,383
	30- 60	228 / 68	7.7 / 8.2		1,770 / 2,647	46 / 32	269 / 367	3,700 / 4,181
	60- 90	197 / 37	6.6 / 4.5		1,075 / 1,412	46 / 26	221 / 294	4,533 / 6,124
	90-107	106 / 8	3.6 / 1.0		570 / 1,094	47 / 106	147 / 273	3,148 / 5,719
	0-107	2,858 / 831	96.5 / 100.1		9,209 / 8,682	346 / 214	1,124 / 1,164	17,964 / 18,407
Fertilized - Unfertilized		2,027			527	132	-40	-443

Source: Adapted from Tables 1 and 2 of Fehrenbacher and Snider (1954).

Note:

*Data are from fertilized/unfertilized plots.

**Values are for constant depths using data from soil horizons.

Table 6b. Yield, Chemical Composition, and Mass of Corn Plant Parts on Fertilized and Unfertilized Cisne Silt Loam. *

Soil treatment	*Plant part*	*Yield (bu ac^{-1})*	*Dry matter (kg ha^{-1})*	*N*	*P*	*K*	*Ca*
				% nutrient in plant/kg plant nutrient ha^{-1}			
Fertilized	Stalk		4,050	0.98 / 39.7	0.18 / 7.3	1.62 / 65.6	0.52 / 21.1
	Leaves						
	Leaf leachate						
	Grain	75	4,699	1.80 / 84.6	0.44 / 20.7	0.26 / 12.2	0.09 / 4.2
	Cob		1,119	0.40 / 4.5	0.09 / 1.0	0.41 / 4.6	0.10 / 1.1
	Root exudate						
	Root (0- 23 cm)		1,939	0.68 / 13.2	0.16 / 3.1	1.61 / 31.2	0.40 / 7.8
	Root (23-140 cm)		1,023	1.28 / 13.1	0.07 / 0.7	0.95 / 9.7	0.55 / 5.6
	Root (0-140 cm)		2,962	0.89 / 26.3	0.13 / 3.8	1.38 / 40.9	0.45 / 13.4
	Total		12,830	155.1	32.8	123.3	39.8
Unfertilized	Stalk		1,768	0.92 / 16.3	0.10 / 1.8	0.40 / 7.1	0.55 / 9.7
	Leaves						
	Leaf leachate						
	Grain	20	1,253	1.54 / 19.3	0.40 / 5.0	0.26 / 3.3	0.10 / 1.2
	Cob		380	0.46 / 1.7	0.11 / 0.4	0.81 / 3.1	0.06 / 0.2
	Root exudate						
	Root (0- 23 cm)		679	0.72 / 4.9	0.10 / 0.7	0.34 / 2.3	0.30 / 2.0
	Root (23-140 cm)		152	1.16 / 1.8	0.19 / 0.3	0.51 / 0.8	0.47 / 0.7
	Root (0-140 cm)		831	0.81 / 6.7	0.12 / 1.0	0.37 / 3.1	0.32 / 2.7
	Total		2,464	44.0	11.0	16.6	13.8
Yearly harvest: Fertilized − Unfertilized			+6,920**	-65.3	-15.7	-8.9	3.0

Source: Adapted from Table 3 of Fehrenbacher and Snider (1954).
Notes:
*Data are from fertilized/unfertilized plots.
**Net measured corn organic matter left and on the field.

Fertilization-enhanced depletion of subsoil nutrients was further illustrated by analysis of the 51-year-old grain plots of the Aledo Soil Experimental Field in west-central Illinois — Sable soil, poorly drained prairie loess soil with tile drainage. Relative to the unfertilized plots, the adequately, but not most-heavily P-fertilized plots increased P in the 0 to 20 cm plow layer by 511 kg ha^{-1} (Table 7). Looking at P content in the plow layer leads one to conclude that P fertilization enhanced soil P fertility.

The Sable subsoil tells a different story, however. At soil depths between 20 to 91 cm, P content is 527 kg ha^{-1} less in the fertilized plots than in the unfertilized plots (Table 7). These results are consistent with fertilizer treatment stimulating root development and enhancing nutrient depletion of the subsoil. The Aledo Soil Experimental Field P fertilizer treatment appears unable to sustain long-term crop production as subsoil impoverishment is not the road to sustaining crop yields.

The Fehrenbacher and Snider (1954) Cisne soil experiment was extended to other Illinois soils and crops:

"We studied the characteristics and yields of five contrasting soils. These were silty loess (Muscatine and Flanagan), a loamy till soil (Saybrook), a clayey till soil (Clarence), and a silty-clayey, high sodium claypan soil (Huey)" (Fehrenbacher et al., 1969, p. 14).

The four crops studied were corn, soybean, wheat, and meadow (alfalfa, timothy, and red clover):

"Fertilizing claypan soils, which are naturally low in fertility, caused striking increases in root penetration and yield of the four crops" (Fehrenbacher et al., 1969, p. 18).

The same effect was reported for heavy soils (Fehrenbacher et al., 1969). Whereas chemical and plant soil profile data were not published, the published results were similar to those for the earlier legume rotation fertilization research on Cisne silt loam (Fehrenbacher and Snider, 1954).

This synthesis of the literature shows that 19th and 20th century agricultural practices have resulted in a decrease in SOC in the plow layer in addition to losses of SOC during the period between when the American Natives were displaced from the land and the European settlers began to plow the prairie and forest soils of Illinois. It also shows the importance of accounting for loss of SOC from the soil below the plow layer. The literature from the late 20th century reports increases in surface SOC when tillage is changed from plowing to low- and no-till practices. However, studies indicate that surfaced-applied fertilizers encourage deeper root

Table 7. Average Total P Values for Sable Soil 400 Series Grain Plots, Aledo Soil Experimental Field, Mercer County, Illinois.

Soil depth	*Total P (kg ha^{-1})*	
(cm)	*Unfertilized control*	*P fertilized*
0-20	1,180	1,692
20-30	552	524
30-61	1,251	1,133
61-91	1,757	1,406
	4,740	4,755

Source: John (1962).
Note:
Results are after 51 years of P treatments.

growth with associated depletion of nutrients and SOC from the deeper soil layers. Because 85 percent of the SOC in the top 1 m is located below 15 cm, the loss of SOC from this soil nutrient depletion can overwhelm the SOC sequestered in the top 15 cm.

Agricultural Management Practices to Sequester Soil Organic Carbon

Given the ambivalence of no-till in the net sequestration of C in Illinois soils, synthesis of the literature from the preceding sections is continued to identify agricultural practices to sequester SOC throughout the whole-soil profile.

Soil genesis and the history of agriculture show that external inputs of mineral nutrients are essential for both sustained crop production and cropland SOC sequestration. The Illinois soil development sequence — the aging of SOC-rich soils to SOC-poor soils — is a useful how-to guide for SOC sequestration. One key factor in the decline of SOC with soil aging is the decline of nutrients over time. Conversely, to optimize crop biomass production and enhance SOC sequestration, agronomic practices need to optimize plant-available nutrients, water, and microclimate.

From the earliest times of scientific agriculture it was recognized that agricultural practices can either accelerate the soil aging process by mining soil of its SOC or they can reverse the soil aging process to rejuvenate soil by adding mineral nutrients and sequestering SOC (Snyder, 1905; Hopkins, 1906, 1907, 1908, 1910, 1913; Conner, 1922; Albrecht, 1938; DeTurk, 1938; Whiteside and Smith, 1941; Viets and Hageman, 1971; Odell et al., 1984a; Stevenson, 1986). A prominent example is the Morrow Plots experiment where liming and addition of N, P, and K to unfertilized corn-oat-clover rotation starting in 1955 — whose plow-layer SOC stabilized at a high level compared to that of unfertilized continuous corn (Table 8) — restored an estimated 6.5 metric tons SOM (3.7 metric tons SOC assuming SOM = 1.752 SOC) to the plow layer by 1964 over what it would have been if left unfertilized (Odell et al., 1984b). As noted by Jenny (1941), using the whole range of management tools available, given proper fertilizer, organic additions and cultural practices, agriculture theoretically can increase cropland SOC to amounts greater than inferred pre-agricultural levels. Such promise is suggested by a whole-soil profile study in Ohio that showed that some cropped lands in Ohio have higher whole-soil profile SOC contents than their virgin control counterparts (Smith and Young, 1975).

Table 8. Morrow Plots, Plow Layer Soil Organic Carbon Content of Continuous Corn and Corn-Oats-Clover Rotation, 1904-1933.

Year	*Continuous corn SOC Content (metric tons ha^{-1})*	*Corn-oats-clover SOC Content (metric tons ha^{-1})*
1904	47.2	57.7
1913	45.4	57.3
1923	40.3	55.9
1933	38.7	58.1

Source: 1904 -1933 data from DeTurk (1938).

Millette et al. (1980) also observed greater SOC storage in cultivated Quebec soils relative to their forested counterparts.

Anthropogenic fertilization can act as a geologic agent to increase natural fertility (and increase C and N content of soils above their natural levels) in nutrient-poor geologic terrains — landscapes poor in P and other mineral nutrients as a function of inherent composition of parent material or effective soil age (Hopkins, 1910; Jenny, 1941; Walker and Adams, 1958, 1959; Walker et al., 1959; Cole and Heil, 1981; Haynes and Naidu, 1998). Implicit to such a manipulation of the geologic soil-forming factor is the potential to take post-mature soils and build up their SOC content to amounts greater than presettlement levels by increasing the fertility of the whole-soil profile. In the Illinois soil development sequence, such manipulation appears to be especially promising for post-mature prairie soils (Hopkins, 1910; Figure 2).

The necessity of appreciable external nutrient inputs to sustain agricultural productivity is evidenced by agricultural history. Where farmers already were putting in external nutrients (such as ashes, lime, gypsum ($CaSO_4$), and manures), these inputs were usually not enough. As noted by Hopkins (1907, 1908, 1910, 1913) and others (Hopkins and Reidhimer, 1907; Davenport, 1908; Hopkins and Pettit, 1908), all forms of agriculture — including crop rotations including legumes, and crop rotations mixed with grazing — in the absence of sufficient and balanced external inputs of mineral nutrients, deplete the soil, e.g.:

"The historical facts are, that the practice of agriculture has reduced the productive power of soils in all extensive[ly] agricultural countries, including China, India, Russia, and the eastern part of our own United States" (Hopkins, 1908, p.2).

"The fact that clover was grown for generations on lands of the older eastern states until the clover crop itself finally failed on millions of acres now agriculturally abandoned is overlooked or forgotten by present-day farmers, especially the descendants of those who have gone west and settled on new, rich lands" (Hopkins, 1913, p. 31).

"...it is common knowledge that even in this new rich State of Illinois the lands that have been under cultivation for half or three-quarters of a century are much less productive now than they once were" (Hopkins, 1907, p. 2).

"When the clover system fails, as it has failed always in older countries, and as it is failing now on the older lands of Illinois, it has been common for the younger men to leave the old farms, either to go farther west or to the cities" (Hopkins, 1908, pp. 1-2).

"...it must be confessed that on the average Illinois is producing only 16 bushels of wheat and 36 bushels of corn to the acre, which is less than half a crop, measured by the possibilities of our soil and climate" (Hopkins, 1913, p. 76).

Early recognition of the necessity of significant and balanced inputs of external nutrients for sustainable agriculture is witnessed by Liebig's Law of the Minimum and by the experiments carried out at the earliest permanent agricultural experimental plots (e.g., the Rothamsted Experiment Station and the Morrow Plots). Indeed, even prior to the establishment of Rothamsted, one of Rothamsted's founders, Sir John Bennet Lawes, initiated the superphosphate fertilizer industry by inventing superphosphate fertilizer and the process used to make it commercially by treating rock phosphate with sulfuric acid. Lawes received a patent for the process in 1842 (Martin and Wilding, 1937, pp. 543-544).

Nutrients are necessary to grow the crop biomass to be incorporated into the soil. And nutrients beyond that needed to grow crop biomass are necessary to most efficiently sequester incorporated crop biomass as humified SOC. The three nutrient elements needed in greatest quantity to sequester SOC are N, P, and S (Cole and Heil, 1981; Stewart, 1984; Parton et al., 1988):

"Soil organic matter in the A horizon tends to contain carbon, nitrogen, sulphur and phosphorus in the approximate proportions of 100:8:1:1.2.... A deficiency of either nitrogen, sulphur or phosphorus will tend to restrict growth and the accumulation of organic matter, and as only a small fraction of the organic nitrogen, sulphur and phosphorus will mineralise annually, continual supplies are necessary during the phase of organic matter accumulation. If a deficiency of phosphorus is the first factor to limit growth, then in the absence of intense P-fixation in the organic form a high proportion of the soil phosphorus should be in organic form.... With regard to sulfur, in well drained soils which have undergone sufficient weathering the only additional source will be atmospheric returns. As only 1 pound of sulphur per acre per annum [1.1 kg S ha^{-1} yr^{-1}] may be returned in some areas of the world..., sulphur supplies may sometimes limit the rate of accumulation of organic matter, especially where legumes contribute appreciably to production, as large amounts of sulphur and phosphorus are needed, and one or both of these nutrients may need to be applied..." (Walker, 1956, pp. 409-410).

Researchers use legumes to test for sulfur-deficiency because of their long-known responsiveness to S (e.g., Brown and Kellogg, 1915; Alway, 1940; Seim et al., 1969; Martin and Walker, 1966; Beaton et al., 1971; Hoeft et al., 1972; 1973; Hoeft and Walsh, 1975; Zhao et al., 1999):

"Mayer communicated the results of his experiments to the Economic Society of Bern: these appeared to be so extraordinary that they had them repeated in the following year before two special commissioners. On the 28th of February, 1768, gypsum was spread on part of a field of clover....

"On May 7 the plastered [gypsum-fertilized] clover, by its dark green color, distinguished itself in an astounding manner from that which surrounded it.

"Finally, cut on June 17, it was 104 cm high and very vigorous. That which had not been plastered was (only) 35 to 50 cm in height and had a yellowish color. Other trials made on clover sown with oats the preceding year also gave good results.

"After this time the use of gypsum spread in a truly extraordinary manner.... However, it is especially in the United States that the (land) plaster has come into such common use that each year an immense quantity is imported....

"This introduction of gypsum to the United States dates from the memorable experiment made by B. Franklin. In spreading the plaster on a field of alfalfa situated beside a main road, near Washington, he traced the forever celebrated words: *This has been plastered*. The effect produced on the meadow was such that these words could be easily read by travelers passing on the road" [Alway, 1940, p. 914 (emphasis his)].

The typical practice of the time was to "improve" the soil by growing crops in legume rotation. The soil would eventually wear out, and mineral fertilizers were added, one of which was gypsum ($CaSO_4$). Application of $CaSO_4$ was done around the time of legume planting. Like today, the best response of S addition was seen on light, sandy soils rather than heavy soils (Cooper, 1794, pp. 124-125). If added in sufficient quantity, $CaSO_4$ enhances legume growth in mixed grass ecosystems even when N fertilizers are added (Walker and Adams, 1958).

Ashes, from time immemorial (e.g., Hopkins, 1913, p. 18), were universally used as a mineral fertilizer in legume crop rotations:

"I should have observed before, that in *England* Peat Ashes bring forth Clover Grass in an extraordinary Manner, and so sweetens the Ground that let the grass be ever so Rank, yet the cattle eat it with eagerness before other grass" [Eliot, 1760, p. 48 (emphasis his)].

From the earliest colonization of America (Eliot, 1760; Cooper, 1794, p. 143; Smith, 1937) and into the 20th Century, farmers found that application of ashes in the absence of dung ensured prolific legume growth:

"Wood ashes make an excellent top dressing for grass lands, particularly where it is desired to encourage the growth of clover [a legume]" (Snyder, 1905, p. 185).

Ashes were bought and sold as an agricultural commodity until after the Civil War. Also, ashes were processed into potash and sold as fertilizer for domestic and foreign export (Eliot, 1760; Cooper, 1794, p. 143; Smith, 1937; Russell, 1976, pp. 130, 271):

"Much of the profit in the use of lime, phosphate and potash is in the beneficial effect on legumes, thus indirectly these materials act as nitrogenous fertilizers" (Conner, 1922, p. 182).

Early experiments from Rothamsted report that the effect of mineral fertilizers (P, K, Na, Mg, and $CaCO_3$), in the absence of N fertilizer, "rather diminished the proportion of the grasses, and considerably that of the weedy herbage; greatly increased the amount per acre, and the proportion in the produce, of the Leguminous herbage..." (Lawes and Gilbert, 1863, pp. 131-132).

These early experiments were continued for more than a century:

"Even after 130 yr, yields...and species composition of some of the plots are still changing. The unmanured plots have the richest flora...with many grasses, a few legumes, and many broad-leaved weeds, but none grows vigorously and yields are small. The plot receiving P, K, Na, Mg, and $CaCO_3$, now produces almost as much dry matter...as the plot receiving N (144 Kg ha^{-1} yr^{-1}), P, K, Na, Mg, and $CaCO_3$, presumably because of symbiotic N fixation by the legumes it contains" (Jenkinson, 1991, p. 8).

The classic text *Soils and Fertilizers* noted the following about a century ago:

"For leguminous crops potash and lime fertilizers have been found to be of most value...as the results of growing leguminous crops...the soil is enriched with nitrogen and the phosphoric acid is changed to available form" (Snyder, 1905, p. 226).

In Minnesota, it was found that by including clover in the wheat-oats-corn crop rotation that instead of losing 164 kg N ha^{-1} yr^{-1} from the soil, the soil gained 68 kg N ha^{-1} yr^{-1}. Total improvement in N status when including N in harvested crops was 235 kg N ha^{-1} yr^{-1} (Snyder, 1905, pp. 112-114).

In the Chapter, "Formation of Soil" in *Soils and Men. Yearbook of Agriculture 1938*, the USDA aptly summarized:

"In the presence of lime (calcium) the legumes use other elements more effectively, such as phosphorus and probably other nutrients. Thus heavier production results in soils rich in minerals, including more intensive and extensive root development — the most effective means of introducing organic matter into the soil.... If the soils that have lost their organic matter are to be restored, the losses of minerals, which has probably been fully as great, must be taken into account, and provision must be made to restore these mineral deficiencies before attempting to grow crops for the sake of adding organic matter" (Albrecht, 1938, p. 357).

Continuous fertilization of Rothamsted's Broadbalk Field wheat experiment since 1844 has increased SOC and soil N in proportion to the rate of soil N fertilization:

"The use of fertilizer N has increased N mineralization due to the build-up of soil organic N" (Glendining et al., 1996, p. 347).

It has been long known that too heavy an application of fertilizer stunts root growth, keeping roots concentrated in the heavily-fertilized surface soil making crops especially susceptible to periods of deficient moisture (Weaver et al., 1922; Scarseth et al., 1943; Barley, 1970). In addition subsoil depletion of SOC and nutrients was a concern. Accordingly, long-term experiments were conducted on the movement of $CaCO_3$, P, K, and N fertilizers into the subsoil and, indirectly, sequestration of SOC of some permanence in the subsoil.

The *Illinois Agronomy Handbook* summary of research on modern fertilizers concludes that $CaCO_3$, P, and K fertilizers are essentially immobile and do not move down into the soil profile:

"Phosphorus and potassium fertilizers and limestone are not mobile in the soil; they remain at or near the soil surface unless they are moved by a tillage operation. This movement is least with a no-till system and greatest when soils are moldboard plowed. Research has shown that surface-applied fertilizers remain in the upper 2 inches [5 cm] of soil with no-till; in the upper 3 to 4 inches [7.5 to 10 cm] with chisel plow or disc tillage; and are uniformly distributed throughout the plowed layer when the tillage system includes moldboard plowing. Roots can use nutrients placed close to the surface with conservation tillage because the crop residue mulch tends to keep soil moist" (Boone et al., 1978, p. 50).

Therefore:

"With continued reduced tillage practices, soil fertility at deeper levels may be depleted such that future fertility practices may need adaptation" (Hoeft and Peck, 2000, p. 88).

Since the Illinois subsoil fertility and rooting experiments of the 1950s and 1960s, there has been a dearth of whole-soil research. This coincides with the development of low- and no-till agricultural practices enabled by the development of pesticides and herbicides that reduce or eliminate the need to use tillage to control weeds and allow insect- and disease-harboring residues to accumulate on the surface. Such conservation tillage practices enable the surface soil to be in a less disturbed, more "natural" condition (Phillips et al., 1980). With these new soil conservation techniques came increased focus on the top layer of the plow zone.

Therefore, the soils research of the 19th Century and the early-to-mid 20th Century was examined to obtain information about mobilization of fertilizer into the subsoil. During this period, long-term experiments were conducted on the effect of fertilization on whole-soil profile root penetration, changes in SOC with depth, and movement of fertilizer additions through the soil profile.

Long-term fertilizer experiments of the past discovered various agronomic practices by which surficially applied fertilizers are moved through the soil profile to enrich the subsoil. For example, Dyer (1901) reported on soil and drainage water P and K data collected from 1844 through 1893 for Rothamsted's heavy, clayey wheatfields of Broadbalk Field. Soils were sampled from 0 to 23 cm, 23 to 46 cm, and 46 to 91 cm depths and analyzed for nutrients. Drainage water collected in drainpipes at 91 cm depth was also collected and analyzed for P and K. Analyses showed that with various fertilizer treatments, fertilizer additions of P and K move into and accumulate in all three soil layers. Furthermore, P and K moved through the 91 cm of soil, some exiting through the drainpipes with the remainder moving down into the underlying soil. Salts of SO_4^{2-} and chemical N fertilizer enhanced the leaching of P and K deep into the soil. Animal manure was especially effective in mobilizing P. Dyer (1901) speculated that the increased earthworm activity seen in the manured plots probably facilitated P mobilization.

Dyer (1902) noted that with complete fertilizer (N, P, and K), not only did N move through and accumulate in the Rothamsted soil profile in the long-term under wheat, but so did P and K. For example:

"In connection with the 1893 results, the solvent action of alkaline salts on the phosphates of the subsoil was pointed out...distinct evidence of accumulation in both the second [23 to 46 cm] and third [46 to 91 cm] depths between 1881 and 1893, owing to descent of mineral phosphates" (Dyer, 1902, p. 137).

Dyer (1902) also noted:

"On plats 11, 12, and 14, which received ammonium salts and phosphates without potash, there is in the surface soils [0 to 23 cm] a uniform diminution between 1865 and 1893.... If we compare the 1865 and 1893 figures for the second [23 to 46 cm] depths of the same plats we also see, on the whole, a diminution.

"When the results for the potash-manured plat (13) are examined the effect of the potash salts is strikingly seen in all three sets of samples not only in the first depth [0 to 23 cm] but also in the second 9 inches [23 to 46 cm]. In the third 9 inches [46 to 91 cm] the difference is clearly apparent only in the 1893 samples" (p. 139).

Later studies supported results of the 19th Century Rothamsted long-term experiments that mobile constituents helped move otherwise immobile nutrient elements down into the soil profile.

Metzger (1934) researched the P mobility of different fertilization treatments for continuous alfalfa grown in Derby silt loam — loess-derived soil at the Kansas Agricultural Experiment Station in Manhattan. Given that the annual rainfall averages 79 cm yr^{-1}, and that 75 percent of it falls during the 6 month period of April to September, the high evaporation during this period of the year plus the high water requirement of alfalfa "placed a decided restriction on ground water penetration in the soil under this alfalfa sod" (p. 625). And:

"Since the alfalfa received no cultivation, the fertilizer nutrients applied had no means of penetrating to the lower depths of the soil except by downward movement with percolating ground water or translocation downward in the roots of plants" (Metzger, 1934, p. 620).

During the first 14 years of treatment, there was little movement of P down the soil profile with application of superphosphate alone, most applied P being confined to the top 5 cm of soil. However, there was significant movement of P down the soil profile when mixed with other fertilizer substance(s), especially complete fertilization:

"Movement of phosphorus is indicated throughout the profile in the complete fertilizer plat.... This type of movement has been demonstrated by...others" (Metzger, 1934, p. 624). Greater rates of nutrient uptake also were observed in mixed- and complete-fertilizer treatments (Metzger, 1934).

After 27 years, even soil treated by superphosphate alone accumulated easily soluble and total P down to the full measured depth of 91 cm (Table 9):

"There appeared to be accumulated phosphorus to depths of 2 to 3 feet [61 to 91 cm]...in plats treated with rock phosphate and manure and with lime and manure and, to a lesser extent in the superphosphate plat. Potash or potash and sodium nitrate applied with superphosphate resulted in more complete utilization of the phosphorus by the plants than did the superphosphate used alone" (Metzger, 1939, pp. 25-26).

Manure contained P, and manure P penetrated deeply into the soil (Metzger, 1939). The effect was enhanced when $CaCO_3$ was added along with manure:

"It appears that liming not only brought about the retention of a considerable quantity of applied phosphorus [in manure] in the soil but it also aided its penetration" (Metzger, 1939, p. 19).

Table 9. Accumulated Total Phosphorus by Treatment as Percentage of Native Soil Phosphorus.

Depth (cm)	*Superphosphate*			*Manure*			
	Only	*+ K_2SO_4*	*+K_2SO_4 +$NaNO_3$*	*2.5 tons + rock phosphate*	*2.5 tons*	*5 tons*	*2.5 tons*
0-10	28	17	36	191	4	9	22
10-15	41	18	17	134	13	22	3
15-23	18	7	28	87	3	21	10
23-30	19	12	11	19	4	9	13
30-46	3	—	10	2	4	6	17
46-61	8	—	5	3	—	2	38
61-91	4	—	—	—	1	—	25

Source: Modified from Table 4 of Metzger (1939).

Long-term fertilizer farm restoration experiments were conducted in the early 20th Century on three representative farm types of Illinois (Thor, 1933).

The Hopkins “Poorland Farm,” located in south-central Illinois, had gray silt loam soil with a tight clay subsoil at a depth of 46 cm. Unlike the other two farms examined, this farm was not a typical Corn Belt farm. It had been abandoned in 1899 because it would only grow poverty grass, red sorrel, and weeds.

The Meis Farm, located in Livingston County in north-central Illinois, had Brenton silt loam, sandy phase soil underlain with coarse sand at 91 to 102 cm. It was a Corn Belt farm on level, well-drained prairie soil with relatively high SOM content and good surface and subsurface drainage and strong acidity.

The Mann Farm, located in Iroquois County in north-central Illinois, had Muscatine silt loam soil. It too was a Corn Belt farm on level, well-drained prairie soil with high SOM content and good surface and subsurface drainage and slight acidity.

The Hopkins “Poorland Farm” represented the widespread problem in American agriculture of attempting to farm on highly aged, post-mature soils:

“The problem of highly acid subsoils restricting plant root growth has long been recognized and is possibly much greater than previously thought.

“Since lime moves slowly in the soil profile, it is beneficial only in the immediate vicinity of application. Thus, surface-applying lime without some degree of mixing in the soil is not effective in correcting subsoil acidity” (Doss et al., 1979, p. 541).

However, the long-term liming experiment at the Hopkins “Poorland Farm”showed that but modest additions of lime totaling 11.2 metric tons ha^{-1}, ~0.4 metric ton lime $ha^{-1} yr^{-1}$, reduced the pH measure of acidity throughout the measured depth of soil, 53 cm. The liming-alone treatment increased N-inferred SOC down to a depth of 36 cm. No decrease in any measure of soil nutrients was detected at any depth even though crop yields and nutrients exported were increased relative to the unfertilized treatment (Table 10).

Liming plus modest application of rock phosphate increased N-inferred SOC and all measures of soil nutrient status throughout the 53 cm measured depth of soil, while further increasing harvest relative to that of the no-fertilizer treatment. Rock phosphate further reduced soil acidity relative to the lime-alone treatment (Table 10; Thor, 1933), much as $CaSO_4$ does.

Application of $CaSO_4$ — a neutral salt which has no acid-neutralizing capacity — interacts with ionic aluminum (Al), and other hydrolyzing acid cations, in a manner which has long been described as a “self-liming effect” (e.g, Kotze and Diest, 1975). Application of $CaSO_4$ reduces Al toxicity of subsoil by ligand exchange of SO_4^{2-} for hydroxyl (OH^-) of sesquioxides which produces alkalinity and also precipitates ionic Al as basic aluminum sulfates. The same interactions occur between phosphate anions and sesquioxides (Hsu, 1977; Schwertmann and Taylor, 1977).

After fertilization with limestone, and rock phosphate and limestone from 1904 to 1920, good crop yields were maintained by both fertilizer treatments at the Hopkins “Poorland Farm.” Additionally, the enhanced biological productivity promoted by fertilization enhanced mineral weathering and transformed unavailable native phosphate to biologically-available form.

Hopkins “Poorland Farm” data suggest that agronomic practices very well may have been sequestering SOC in naturally SOC-poor, post-mature soils as well as forest soils. For example, growing hay on forest soil in Alberta, Canada from 1936 to 1990 increased SOC 180 percent in the top 15 cm. Continuation of hay cropping was estimated to eventually increase SOC 290

Table 10. Effects of 1904-1920 Soil Treatments on pH, Readily Soluble and Total Phosphorus (P), Available Potassium (K), and Total Nitrogen (N) by Soil Depth and Effect on Crop Yields and P Removed by Hopkins "Poorland Farm" Crops, Marion County, South-Central Illinois, 1931.*

Treatment	*pH*	*Readily soluble P (kg ha^{-1})*	*Total P (kg ha^{-1})*	*P removed by crops (kg ha^{-1})*	*Available K (kg ha^{-1})*	*Total N (kg ha^{-1})*	*Crop yield*				
							Corn (bu ac^{-1})	*Wheat (bu ac^{-1})*	*Oats (bu ac^{-1})*	*Alfalfa or clover (kg ha^{-1})*	*Cowpeas (kg ha^{-1})*
None				—			13	11	—	—	1,860
0-18 cm	4.5	31	—		115	2,887					
18-36 cm	4.4	27	—		84	2,215					
36-53 cm	4.3	11	—		79	1,007					
		69	895		279	6,109					
Total lime - 11,200 kg ha^{-1}			—				31	28	—	—	3,130
0-18 cm	6.8	90	—		119	3,245					
18-36 cm	4.8	36	—		92	2,394					
36-53 cm	4.5	13	—		78	1,007					
		139	906		289	6,646					
Total lime - 11,200 kg ha^{-1}			119				35	35	—	—	3,360
Total P - 560 kg ha^{-1}											
0-18 cm	7.2	340	—		152	3,401					
18-36 cm	5.5	98	—		88	2,484					
36-53 cm	4.8	18	—		115	1,029					
		457	1,231		356	6,915					

Source: Adapted from Tables 3, 4, and 6 of Thor (1933).

Notes:

*Soil values are composites of 20 soil samples. Readily soluble P was determined by the Truog method: 0.002 N H_2SO_4 buffered at pH 3 with $(NH_4)_2SO_4$, 0.5 g soil in 200 ml extractant.

percent over the starting level and 26 percent higher than native SOC content (Izaurralbe et al., 2001).

Data from the Meis Farm show that liming and P treatment raised pH, P, K, and N and N-inferred SOC of the worn-out 0 to 20 cm plow layer relative to the no-fertilizer treatment. It also increased N, N-inferred SOC, and P throughout the 61 cm measured depth of soil while increasing harvest (Table 11; Thor, 1933). Later, more abbreviated research on crop rotation and fertilization effects on soil were tested at the Morrow Plots in Urbana, Illinois (Table 12; Guernsey et al., 1969; Odell et al., 1984a). Throughout the measured depth of the soil profiles, 144 cm, SOC was greater in the corn-oats-clover rotation plot fertilized since 1955 than the unfertilized continuous corn plot (Table 12). Whereas the fertilization treatment is reported to have increased SOC in the top 17 cm between 1955 and 1964 (Odell et al., 1984b), published data have not been found that show the difference fertilization may have had on SOC deeper in the soil profile in addition to that of crop rotation.

The N-inferred SOC in the Muscatine silt loam of the Mann Farm is more concentrated at the surface and drops off more rapidly with depth compared to the central Illinois Corn Belt soil of the Mies Farm (Table 11 and 13). At the Mann Farm, the liming plus P treatment reduced N-inferred SOC relative to the liming-alone treatment in the top 41 cm of soil. However, liming plus P treatment increased N-inferred SOC at depths below 41 cm (Table 13). Liming plus P treatment reduced plant-available K throughout the measured soil profile, while increasing P throughout the soil profile relative to treatment by lime alone (Table 13; Thor, 1933).

The Mann Farm results are similar to the forest soil/cropped soil comparisons made in Ohio (Smith and Young, 1975). They are also similar to the study of 15 comparative forested and cultivated sites in Ontario, Canada, distributed across the major areas of agricultural production (Ellert and Gregorich, 1996). The Ontario study showed that SOC of the top 26 to 32 cm of cultivated soil was 34 percent less than that for forest soil (that included forest floor SOC). The underlying 12 cm subsoil of cultivated soils had 10 percent more SOC than forested counterparts. Results of these Illinois, Ohio, and Canadian research studies (Thor, 1933; Smith and Young, 1975; Ellert and Gregorich, 1996) indicate that the cropping of grasses and legumes produces soils more akin to prairie soils than to forest soils. This is evidenced by the increased deposition of C deeper in the soil profile, the change in soil-depth-SOC relationship, and the narrowing of the C:N ratio of forested soils under cultivation — all manifestations of changes from the characteristics of forest soils to those of prairie soils.

The Hopkins “Poorland Farm,” the Meis Farm and the Mann Farm all had the same surprising result: movement of supposedly immobile nutrient elements through Illinois soil profiles apparently in the absence of mobile carriers. Such unexpected fertilizer nutrient mobility may be due to the inadvertent presence of relatively large amounts of two mobile anion carriers — SO_4^{2-} and NO_3^- — with SO_4^{2-} being especially effective in moving P, K, and lime downward into soils (Dyer, 1901, 1902; Midgley, 1931; Stephenson and Chapman, 1931; Thor, 1933; Weisre, 1933; Metzger, 1934, 1939).

Regarding NO_3^-, incorporation of legume biomass in crop rotations has been shown to be capable of producing appreciable NO_3^-. Whiting and Schoonover (1920, pp. 43-44) report that with 76 mm of rain between March 10 and March 22, 1917, the 0 to 17 cm plow layer of cornfields on the North Farm of the University of Illinois at Urbana-Champaign lost 24.3 kg NO_3-N ha^{-1}. Assuming no water losses to evapotranspiration and no N losses to denitrification (counteracting errors), 76 mm of precipitation produced 76 mm of runoff with an average of 31.9 mg NO_3-N per liter (L^{-1}).

Table 11. Effects of 1913-1920 Rock Phosphate and 1925 Dolomitic Lime Treatments on pH, Readily Soluble and Total Phosphorus (P), Available Potassium (K), and Total Nitrogen (N) by Soil Depth and Effect on Crop Yields and P Removed by Mies Farm Crops, Livingston County, North-Central Illinois, 1931.*

Treatment	*pH*	*Readily soluble P (kg ha^{-1})*	*Total P (kg ha^{-1})*	*P removed by crops (kg ha^{-1})*	*Available K (kg ha^{-1})*	*Total N (kg ha^{-1})*	*Crop yield*				
							Corn (bu ac^{-1})	*Wheat (bu ac^{-1})*	*Oats (bu ac^{-1})*	*Alfalfa or clover (kg ha^{-1})*	*Cowpeas (kg ha^{-1})*
None				—			39	21.5	31	Failed	—
0-20 cm	4.9	28	—		358	4,880					
20-41 cm	5.8	20	—		384	4,450					
41-61 cm	5.9	16	—		373	3,490					
			64	1,140	1,114	12,820					
Total lime - 8,950 kg ha^{-1}				168			52	29.5	48	4,480	—
Total P - 840 kg ha^{-1}											
0-20 cm	6.0	442	—		451	5,560					
20-41 cm	5.9	56	—		391	5,210					
41-61 cm	5.8	40	—		368	3,920					
		538	1,634		1,210	14,690					

Source: Adapted from Tables 1, 4, and 6 of Thor (1933).

Notes:

*Soil values are composites of 9 soil samples. Readily soluble P was determined by the Truog method: 0.002 N H_2SO_4 buffered at pH 3 with $(NH_4)_2SO_4$, 0.5 g soil in 200 ml extractant.

Table 12. Soil Organic Carbon Content, Weight of Corn Root, and Porosity of Morrow Plots Soils under Continuous Corn and Corn-Oats-Clover Rotation in 1964.

Continuous corn					*Corn-oats-clover**				
Soil horizon	*Depth (cm)*	*Organic carbon (metric tons ha^{-1})*	*Porosity (%)*	*Root*** *(g)*	*Soil horizon*	*Depth (cm)*	*Organic carbon (metric tons ha^{-1})*	*Porosity (%)*	*Root*** *(g)*
Ap	0-23	44.02	45.3	6.001	Ap	0-25	67.42	47.5	8.894
A12	23-30	13.98	49.4	2.000	A12	25-46	52.27	50.6	2.062
B1	30-38	13.73	46.0	0.253	B1	46-58	20.83	47.2	0.252
B21t	38-56	16.74	43.4	0.590	B21t	58-74	14.94	39.2	0.202
B22t	56-76	16.96	40.8	0.483	B22t	74-94	9.18	38.1	0.253
B3	76-124	17.63	42.3	0.804	B3	94-114	7.44	36.2	0.328
IIC1	124-147	8.45	34.0	0.041	IIC1	114-175	—	40.8	0.540
IIC2	147-183	8.75	29.4	0.047	IIC2	175-183	—	27.9	0.065
				10.219					12.496
	0-30	58.00 ***				0-30	79.87 ***		
	30-60	33.86				30-60	35.15		
	60-90	8.53				60-90	9.21		
	90-114	8.82				90-114	9.28		
		109.21					133.51		

Source: Adapted from Table 1 of Guernsey et al. (1969) and Table 3 of Odell et al. (1984a).
Note:
*Fertilized with lime, N, P, and K since 1955.
**Corn root weights for 7.6x23x183 cm area under corn hill.
***Mean for constant depths.

Table 13. Effects of 1901-1920 Rock Phosphate and Lime Treatments on pH, Readily Soluble and Total Phosphorus (P), Available Potassium (K), and Total Nitrogen (N) by Soil Depth and Effect on Crop Yields and P Removed by Mann Farm Crops, Iroquois County, North-Central Illinois.*

Treatment	*pH*	*Readily soluble P (kg ha⁻¹)*	*Total P (kg ha⁻¹)*	*P removed by crops (kg ha⁻¹)*	*Available K (kg ha⁻¹)*	*Total N (kg ha⁻¹)*	*Crop yield* Corn (bu ac⁻¹)	*Crop yield* Wheat (bu ac⁻¹)	*Crop yield* Oats (bu ac⁻¹)	*Crop yield* Alfalfa or clover (kg ha⁻¹)	*Crop yield* Cowpeas (kg ha⁻¹)
Total lime - 8,950 kg ha^{-1}				—			45	19	42	2,200	—
0-15 cm	6.4	175	—		429	6,680					
15-41 cm	6.4	56	—		312	5,040					
41-61 cm	6.8	26	—		271	2,190					
		256	1,010		1,011	13,910					
Total lime - 8,950 kg ha^{-1}				454			35	35	65	2,200-4,400	3,360
Total P - 1,120 kg ha^{-1}											
0-15 cm	6.1	417	—		385	5,480					
15-41 cm	6.0	79	—		267	4,140					
41-61 cm	6.0	49	—		233	2,800					
		546	1,750		885	12,420					

Source: Adapted from Tables 1, 4, and 6 of Thor (1933).

Notes:

*Soil values are composites of 9 soil samples. Readily soluble P was determined by the Truog method: 0.002 N H_2SO_4 buffered at pH 3 with $(NH_4)_2SO_4$, 0.5 g soil in 200 ml extractant.

Whiting and Richmond (1921) note that decomposition of clover (a legume) produces large amounts of NO_3^- in a short time, 21 to 28 days, in Illinois:

"From this year's [1919] results on the brown silt loam it is evident that the nitrate production on this type of soil is greatly enhanced by the plowing under of green sweet clover. Another important fact is that approximately one ton (water-free basis) of spring growth of sweet-clover tops, together with the roots and fall residues, furnished as much nitrate as 19.8 tons of average farm manure" (Whiting and Richmond, 1921, p. 261).

The development of cropland management practices has been designed to increasingly minimize the leaching of NO_3-N (e.g., Krug and Winstanley, 2000).

There appears to be a trend of decreased SO_4^{2-} leaching. For most of the 20th Century, acid rain in Illinois provided appreciable SO_4^{2-} to leach into the subsoil:

"The plant demands for sulfur are rather large and the supply in the soil is comparatively small.... Fortunately, however, sulfur is added to the soil by rainfall in amounts sufficient not only to meet the needs of plants but also to offset the loss by drainage water. Definite experimental data covering a period of seven years, obtained at the University of Illinois, show that 40 pounds of sulfur per acre annually [45 kg ha^{-1} yr^{-1}] are brought to the soil in the rainfall" (Stewart, 1920a, p. 5).

Stewart (1920b) noted that, whereas a 6,287 kg ha^{-1} corn harvest removes 10.6 kg S ha^{-1} yr^{-1}, atmospheric deposition of the time supplied 17.9 kg SO_4-S ha^{-1} yr^{-1} during the growing season alone:

"Very fortunate would we be could our phosphorus and limestone problems be so easily solved" (Stewart, 1920b, p. 108).

Iowa, being further west, was subject to lesser amounts of atmospheric deposition of SO_4-S, typically on the order of only 13 to 18 kg SO_4-S ha^{-1} yr^{-1}. Whereas S deficiency was not found in Illinois in the early 20th Century, crop S deficiencies were fairly common in Iowa (Erdman, 1923).

Early scientists, including Benjamin Franklin, recognized that S was essential to plant and crop growth and S fertilizer ($CaSO_4$) was effectively applied on many early farms in the eastern United States (Stewart, 1920b; Sauchelli, 1950). However, by the early 20th Century S deficiency in the eastern United States ceased to be a problem and application of S fertilizer ceased (Stewart, 1920b).

By mid-20th Century, the problem of S deficiency reared its head again:

"In the course of ordinary fertilizer practice, available sulfur has been supplied to the soil in the form of ammonium sulfate, potassium sulfate, and superphosphate. However, with the anticipated increased use of higher-analysis fertilizers these sources of sulfur will be decreased. Thereafter, except for a small reserve in the soil, the chief natural source to growing plants will be brought down in the precipitation.

"With regard to soil reserves...the soils in the United States contain only about 700 pounds of total sulfur/acre [780 kg S ha^{-1}]. This is for the most part insoluble and unavailable at any one time; also, that becoming available is subject to rapid loss by leaching. Thus, the quantity of sulfur brought down by precipitation will become increasingly important" (Fried and Jackson, 1947, p. 19).

Around 1950, "about 12 percent of normal superphosphate was sulfur capable of feeding plants" (Sauchelli, 1950, p. 7), which is about the same as the P content of superphosphate:

"The fact that over the past several years crop deficiencies of S throughout the world have been reported with increasing frequency has focused greater attention on the importance of this element in plant nutrition. These deficiencies of S are occurring probably because of (a) the increased use of S-free fertilizers; (b) the decreased use of S as a fungicide and insecticide; and (c) increased crop yields.... In addition if effective pollution control systems are implemented, there is little question but that the size of the S-deficient areas will rapidly increase and that new S-deficient areas will be found" (Coleman, 1966, p. 230).

In 1972, the *Illinois Agronomy Handbook* reported that Illinois agriculture did not suffer from S deficiency and recommended against application of S fertilizer because "...all Illinois soils appear to be well supplied with sulfur for field crops" (Graffis et al., 1972, p. 48). Later in the 1970s, however, the *Illinois Agronomy Handbook* reported that S deficiency had become a problem:

"Recognition of sulfur deficiency has been reported with increasing frequency throughout the Midwest. These deficiencies probably are occurring because of (1) increased use of S-free fertilizer, (2) decreased use of sulfur as a fungicide and insecticide, (3) increased crop yields, resulting in increased requirements for all of the essential plant nutrients, and (4) decreased atmospheric sulfur supply" (Boone et al., 1978, p. 44). They also recommended testing Illinois agricultural soils for S.

In 1984, the International Society of Soil Science reported that S deficiencies now exist across vast areas of North America, Europe, and Asia (Fox, 1984), e.g.,

"The incidence of sulphur (S) deficiency has increased in many crops in the U.K. [United Kingdom] and other European countries in the last 10 years" (Zhao et al., 1997, p. 1137).

It was noted that:

"Ironically, decreased [atmospheric] S inputs in recent decades have resulted in S deficiency in many agricultural crops in Europe" (Knights et al., 2000, p. 1867).

For the United Kingdom, S deficiency was determined to be a problem in 33 percent of its soils. If the government 2003 target for S emissions is met, S deficiency is predicted to be a problem for 50 percent of United Kingdom soils (McGrath and Zhao, 1995).

It is notoriously difficult to diagnose S deficiency. A plant may appear to be growing as best as it can when it is not because S deficiency often shows no visible symptoms. Even when SO_4-S is removed from the supply, it may take a considerable time for S-deficiency symptoms to develop because plant metabolism continues to draw on residual SO_4-S still present in plant tissues. If S deficiency becomes great enough, then the plant may appear to be N deficient and have low percentages of N. But, if the plant does not respond to N fertilization, then the problem is S deficiency because there is not enough S to incorporate N into plant biomass (Loneragan, 1964; Dijkshoorn and van Wijk, 1967; Hoeft et al., 1985).

Thus, S deficiency may invisibly diminish harvest yield and the supply of plant residue for incorporation in Illinois soils. Additionally, decline in S inputs will diminish the ability of plant residues to become SOC:

"Nitrogen, sulphur, and phosphorus fertilizers have an especially low residual value when applied to newly improved pastures on soils of low organic matter content. This phenomenon is partly a direct result of the striking accumulation of organic matter which takes place under these conditions. Over a very wide range of conditions soil organic matter contains a remarkably constant amount of nitrogen, sulphur, and phosphorus. Thus, the striking increase in the organic matter content of many native grassland soils is accompanied by increases in organic nitrogen, sulphur, and phosphorus. Large amounts of fertilizer may be consumed in supplying the organic forms of these elements...until the organic matter content of these soils reaches a new high equilibrium value, there will be a continual drain on the available forms of nitrogen, sulphur, and phosphorus" (Loneragan, 1964, p. 216).

This effect of decreased S on diminution of SOC sequestration would decrease crop production by decreasing the amounts of other plant-available nutrients and decreasing the favorable physical and biological properties which SOC imparts to soils. This effect of declining S input would not be considered S deficiency because it diminishes crop production by decreasing the supply of other nutrients and by decreasing the physical and biological quality of cropland soil. The S-deficiency-induced effect of decreasing crop productivity due to decreasing chemical, physical, and biological soil quality masks crop S deficiency by decreasing crop demand for S. Viewing the S-limited SOC incorporation problem from the whole-soil perspective, it is not expected that this problem will manifest itself in the plow layer first, but rather in the deepest soil as the uppermost soil takes what S it needs and passes along progressively less S to deeper layers as S input decreases. Since it is at the time of flowering and grain fill that crops derive most of their nutrients and water from the subsoil (Mengel and Barber, 1974; Arya et al., 1975a, b; Emery, 1975; Levan et al., 1987) and at the time when soybeans do most of their N fixation (Harper and Hageman, 1972), the negative effects of decreased S input on crop yields and legume N fixation would be disproportionately severe and would not be recognized as a S-deficiency problem.

Synthesis of the literature in this section shows the importance of plant nutrients throughout the soil profile in maintaining crop biomass productivity. To restore the nutrients in the whole-soil profile, surface applied nutrients must be moved into the deeper soil layers. The literature shows that this can be accomplished using leguminous green and animal manure, and fertilizers using NO_3^- and SO_4^{2-} carriers. Fertile subsoils promote deep, robust root growth and optimize the conversion of root biomass into C sequestered in SOC. The effects of whole-plant/whole-soil interactions must be recognized in order to optimize C sequestration and long-term SOC storage in cropland soils.

Conclusions

Soil organic carbon (SOC) sequestration is important to climate change and cropland agriculture. This report reviewed and synthesized the scientific understanding of SOC sequestration from a soil genesis perspective, and the response of SOC and crops to agronomic practices.

A large body of literature exists that is relevant to the changes of SOC from the time that Native Americans inhabited Illinois to the present. This includes the historic, natural history, prairie and environmental restoration, and agricultural literatures. These need to be located, organized, summarized, and synthesized into the SOC sequestration literature.

The SOC sequestration potential of Illinois soils is determined to be larger than current estimates when the soil-forming, SOC-sequestering conditions of presettlement times are recognized. Soil-forming factors also act rapidly to greatly alter SOC content and quality, and generally lower the estimates of potential-SOC sequestration when using current day prairie and forest natural areas. Furthermore, estimates of cropland-SOC sequestration potential by adopting conservation tillage practices are low, because SOC sequestration potential of the whole-plant/whole-soil interactions of Illinois croplands are not considered. Additionally, the permanence of SOC sequestration by conservation tillage is uncertain. Surficial SOC is subject to greater losses by mineralization and erosion and is more sensitive to changes in tillage practices than is subsoil SOC.

The surficial agronomic perspective on SOC sequestration does not consider the cropland subsoil deterioration and subsequent loss of SOC caused by the export of subsoil nutrients in harvested Corn Belt crops. While modern surficial measurements from low- and no-till practices show SOC increases, studies of SOC and nutrients in agricultural cropland show a loss of SOC that can exceed the SOC increase in the surface layer. Furthermore, most SOC-rich and deep soils are wet soils. Of Illinois' 9.3 million ha of cropland, 4 million ha have been drained, typically to 1 to 1.5 m. These especially SOC-rich drained soils are subject to loss of SOC, both from crop utilization and aeration decomposition.

The preliminary assessment of this report is that organic-rich, deep wetland soils and the richest upland prairie soils in the northern two-thirds of Illinois would have to be returned to their Native American inhabited state to realize their full SOC sequestration potential. Whether SOC levels of these soils can be increased over present levels under the agronomic realities of today is not clear. Research conducted in Illinois 50 to 100 years ago suggest that increasing SOC for fertile Corn Belt soils was possible under some conditions and under the practices of the time.

The SOC potential of post-mature, nutrient-poor, relatively low-SOC soils located in the southern one-third of Illinois may be equaled, or exceeded by agronomic manipulation of soil-forming factors. There are published examples where SOC sequestration potential of post-mature soils are reported to have been exceeded, and this also may have been accomplished inadvertently in some cases in Illinois using the traditional cropping practices of the past. For example, cropping practices may have increased the rate of biomass incorporation into the whole soil over that of the presettlement condition. Crop types and the amount of fertilizer additions may have been sufficient to increase the efficiency of biomass conversion to SOC relative to that of the presettlement condition. Additions of fertilizers and manures that included the mostly inadvertent addition of organic and/or inorganic carriers would have further enhanced biomass additions and efficiency of biomass conversion to soil humus throughout the soil.

However, in the late 20th century, agronomic practices have been designed to minimize nutrient inputs (e.g., Holt, 1989; Benbrook, 1991; Krug and Winstanley, 2000) and mobilization of nutrients needed to sequester SOC throughout the root zone. Fertilizers are either deposited on the surface or shallowly incorporated, i.e., not as deeply incorporated into soil as before, and the chemistry of the applied fertilizers has changed so that lime and fertilizer nutrients are not mobilized deep into the soil. Aboveground plant residues are left on the surface or are partially and shallowly incorporated. Whereas the old practices tended to promote deep and luxuriant root growth, the new practices tend to promote shallow rooting in the concentrated fertilizer zone of the SOC-enriched surface layer which makes crops more susceptible to periods of deficient moisture. Eventually, subsoil impoverishment and fertilizer concentration at the surface will decrease plant productivity, decrease biomass incorporation into the soil, and decrease the efficiency of biomass conversion to soil humus.

These data also have implications for sequestering atmospheric CO_2 and mitigating the greenhouse effect. Topsoil SOC and subsoil SOC are not equivalent. The old subsoil SOC lost has greater permanence than the fresh surficial SOC added. The relative permanence of SOC gained and lost must be entered into the equation and researched.

Research on management practice changes required to enhance SOC sequestration in the whole-soil profile needs to be conducted. The literature indicates that the quickest method involves conversion of land back to native prairie with frequent burning, addition of fertilizer, and elimination of surface and subsurface drainage. Such an approach is not practical. Constraints on optimizing cropland SOC sequestration include: 1) the need to maintain good soil drainage in Illinois soils for timely spring planting that allows for growth of long season corn hybrids and soybean varieties; and 2) maintaining soil nutrient levels that do not result in water-quality issues.

Within these constraints, it is hypothesized that SOC sequestration can best be done by 1) developing balanced soil fertility programs that restore the soil nutrient levels to optimum levels for plant growth, promote movement of plant nutrients throughout the root zone using organic and/or inorganic carriers, and promote deep rooting of plants with minimal mechanical disturbance of the soil by tillage; and 2) developing chemical pest control programs that minimize the effects of pesticides on soil bacteria, microfauna, and macrofauna, thus promoting conversion of biomass to SOC, pedoturbation and net movement of SOC down into the soil profile, and creation of soil structure and aggregation that optimizes biomass production and conversion to stabilized SOC.

Losses of SOC have occurred on the order of the century time scale. SOC sequestration — and the measure of its success (permanence of SOC sequestration) — are also necessarily measured on the order of the century time scale. Therefore, long-term (20 to 30 year) agronomic SOC sequestration research at both the farm and individual plot level needs to be designed and conducted for hypothesis and model testing, as well as evaluation of the permanence of SOC in the surface and whole-soil profile. Even longer-term research needs to be designed and conducted for hypothesis refinement and for monitoring of SOC permanence.

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