Chapter 2

Management Controls on Soil Carbon

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CONTENTS

I. HISTORICAL BACKGROUND

Farmers have long recognized the organic matter content of a soil as a key attribute of soil fertility. It seems likely that this awareness, at least in the intuitive sense of recognizing dark-colored, friable, and earthy smelling soils as favorable sites for growing crops, dates back to the beginnings of agriculture. Yet, the history of agriculture is replete with examples of the depletion of organic matter and the subsequent loss of soil fertility through poor management. In part, this has been due to a lack of knowledge about how various agricultural practices affect the soil. However, it also reflects an inherent conflict between maximizing short-term production at minimal cost vs. providing for the sustained health and long-term productivity of the soil. This tradeoff, between short-term production goals and long-term investment in maintaining soil fertility, characterizes much of the history of agriculture. The development

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of agriculture in temperate regions has exhibited recurrent patterns of exploitative soil use followed by the introduction of regenerative practices as soil resources fell to unacceptable levels. In some cases, severe degradation of the soil led to the collapse of societies and a permanent or long-term loss of productive lands.

A. SOIL CARBON AND EUROPEAN AGRICULTURAL DEVELOPMENT

In central and northern Europe, crop production during Neolithic times was based on swidden or "shifting cultivation" techniques where native vegetation was cleared and burned prior to planting.[1] After a few harvests, fields were abandoned as yields declined and new lands were cleared. While these practices were exploitative in nature, periods of cropping were probably short relative to the fallow period and soil organic matter (SOM) was little affected. Also crop production per se played a secondary role to livestock herding and hunting/gathering in the farmer's livelihood.

Beginning with the influx of Bronze age cultures, larger and more sedentary populations developed and crop production became an increasingly important source of food and fiber. Shifting agriculture practices gradually evolved into a permanent agriculture utilizing the same fields year after year. The introduction of wooden, bronze-, and later iron-shod plows allowed greater areas to be tilled and a greater variety of field crops were grown, including wheat, barley, oats, rye, grain legumes, and forages.[2] It seems likely that the development of metal implements and the use of draft animals had an important stabilizing influence on settlement patterns by improving productivity and making it less practical to continually move onto new lands.[3]

A fair amount is known about agricultural techniques in the Mediterranean region during the Greek and Roman eras from Hesiod, Xenophon, Cato, Varro, Pliny, and other classical writers. The limited and seasonal precipitation necessitated the development of dryland farming with the main cereals being autumn-sown barley and wheat. Grain and forage legumes were also widely used and the benefits of legumes on soil fertility were well recognized.[3] Likewise, the value of animal manure and composts of household wastes were understood and green manuring was a recommended practice. The need for a crumbly soil structure as a seed bed was emphasized by contemporary writers and several plowing and cross-plowings per year were the recommended practice. The Roman writer Cato posed the rhetorical question "Wherein does a good system of agriculture consist? In the first place, in thorough ploughing; in the second place, in thorough ploughing; and in the third place, in manuring."[4]

In Europe, north of the Alps, much less is known about the evolution of permanent agriculture. It appears that the development of the open field system may have begun early in the first millennium of the present era[3] and was well established throughout most of Europe by the Middle Ages.[1] The village or open-field system retained its essential structure until the 16th and 17th centuries and even later in parts of Europe.[5]

In this system, a field was typically cropped for 1 to 2 years and then fallowed for 1 or more years. In the classical three-field system, one field was sown to autumn cereals, one to spring-sown cereals, and the third was fallowed.[3] Fallowed land was cultivated or "stirred" as many as four times per year[2] to prevent weeds and perennial grasses from establishing. Stable manure was spread prior to sowing the first crop after fallow. Outlying meadow and woodland commons were used for livestock grazing and fodder production, which provided a transfer of nutrients and organic matter from meadow to field in the form of manure.[6] While this system provided a basis for permanent agriculture, it still represented extensive land use requiring as much as 50 to 70% of total tillable lands to be kept in fallow.[5]

Farming practices on the cultivated fields were generally poor at maintaining SOM levels. Yields on cropped lands were low and most of the straw was removed for thatching, bedding, fuel, or fodder. The straw which remained was grazed by livestock after the harvest and was sometimes burned. Frequent tillage was necessary for weed control. As populations increased, landholdings became more fragmented and crop production encroached on the grazing commons and marginal lands.[1] With decreased grazing and fodder acreage; less manure was available for spreading on cropped areas. Furthermore, under the feudal system, manure was often reserved for fields under the exclusive control of the manor lord and thus was not available to peasant farmers.[2] Under these conditions soil fertility and productivity, and presumably SOM, declined dramatically. Seebohm[2] states that by the 14th century average wheat yields in Britain had fallen from an average of 10 bushels/acre to 6 bushels/acre due to the "increasing exhaustion of the soil". This loss of productivity is believed to have contributed to the breakdown of the manorial system and the beginning of the end of the village farming system.

Beginning in the 17th and 18th centuries, a number of changes in European agriculture led to gradual but dramatic improvements in soil fertility and productivity.[1] These included the consolidation of landholdings into single farm units, the improvement in plows and replacement of oxen by draft horses, and the introduction of new crops and rotations. With both pasture and cropped lands under the control of an individual farmer and with the availability of grass, clover, and later alfalfa seed, it was possible to rotate forage and cereal production on the same fields, leading to the development of the ley farming system. The introduction of root crops as winter livestock feed and improvements in animal breeding led to increased livestock holdings and thus greater availability of manure. In addition, the practice of composting, utilizing a variety of farm, household, and industrial organic wastes, developed to a high degree.[2] These improvements enabled the use of more sophisticated rotations, with sown hay crops (leys) and legumes alternated with cereals and root crops, providing a basis for continuous production from a given field.

The growth in prosperity and population in Europe, from the 17th century onward, is testament to the increased productivity of these improved farming practices. As an example, one of the early advocates of the new agriculture, the famous French chemist Lavoisier, was able to obtain wheat yields of 20 to 24 bushels/acre (about double the norm in the surrounding district) and maintain five times the normal number of livestock.[3] By the early 19th century improved farming had spread through much of Europe. The use of leys, legumes, and manure additions was well suited for the maintenance of SOM insuring a stable supply of plant nutrients from mineralization. These practices characterized European farming up until this century, when mechanization and the widespread use of chemical fertilizer and pesticides again revolutionized agriculture.

B. SOIL CARBON AND NORTH AMERICAN AGRICULTURAL DEVELOPMENT

Agriculture was an important part of the economy for many of the native North American tribes. Swidden agriculture, similar in form to that practiced in Europe in the Neolithic era, was a predominant practice in the eastern deciduous forests.[7] Trees were girdled in the fall or winter, a practice which was effective for killing the root systems and prevented girdled trees from sprouting.[8] Maize was planted in mounds, with other crops such as beans, pumpkins, squash, and sunflowers interspersed between the maize. Production levels were primarily maintained by periodically abandoning fields and clearing new forest stands, although fish were also used to fertilize maize in coastal regions.[7] As in early Europe, the sparse population and abundant land area meant that agricultural practices per se probably had little impact on SOM. In contrast, the use of fire by native Americans may have significantly influenced prairie ecosystems, and thereby soil development, in the midwest and Great Plains regions of North America (see Chapter 5).

In addition to swidden agriculture, more permanent agricultural fields existed along river systems and in the irrigated agriculture of the Southwestern U.S. Interestingly, investigations of prehistoric fields on runoff terraces in New Mexico by Sandor et al.[9] found that organic matter declines attributable to cultivation were around 50% in the A horizon. This implies that, where more sedentary agriculture was practiced, losses of organic matter and soil degradation due to cultivation could be similar to those which have occurred under industrial-era agriculture.

Following European colonization, agriculture in North America was characterized by a prolonged period of exploitation. Early colonial farming was mainly subsistence based and utilized techniques (i.e., shifting cultivation) and crops — corn, squash, beans, tobacco — adopted from the native peoples. The most important food crop introduced from Europe was wheat. Tillage implements were largely the hoe and planting stick.

In the early European colonies of the Chesapeake Bay region, the typical practice entailed growing one or two crops of tobacco (as a cash crop) followed by several years of maize and then wheat.[8] When wheat yields became unacceptably low, fields were abandoned for 20 to 30 years before again being cleared for a new cropping cycle. While these practices led to soil degradation, particularly during the summer fallow preceding wheat crops,[8] sufficient land areas and a long forest fallow allowed the system to be maintained for many years. However, by the early 1800's population pressures led to an elimination or shortening of the forest fallow period resulting in severe land degradation due to erosion and organic matter loss. A contemporary observer lamented that the low land prices had "greatly contributed to accelerate among our land killers, the exhaustion of our soil."[8] As the unsustainability of existing practices became increasingly apparent, management reforms were introduced. These included the use of grass and clover in rotation with tobacco and grain crops, lime and guano fertilizer applications, and increased livestock holding.[10] However, these reforms were largely restricted to the more densely settled regions and, as population spread westward, the pattern of extensive and exploitative agriculture was repeated.

Social and political forces, as well as technological developments such as the iron and steel plow developed by John Deere in 1837, sparked the rapid agricultural development of the midwest and western U.S. in the 19th century and the Canadian prairies during the late 19th and early 20th centuries. With the expansion of agriculture into the prairie regions, the organic matter-rich soils provided, initially, abundant nutrients and high yields. Organic matter contents of these soils, however, declined in many cases precipitously during several years of continuous cropping.[11] By the end of the 19th century, the frontier was largely closed and a greater emphasis was again placed on the reform of farming practices, primarily directed at rebuilding and maintaining SOM and soil fertility. This is evidenced in part by the establishment of several long-term agricultural field experiments (e.g., References 11 and 12) around the turn of the century.

C. SOIL CARBON AND MODERN AGRICULTURE

During the 20th century, changes in agriculture throughout the temperature regions of the world have been driven by the introduction of fossil-fuel powered machinery, the development of agrochemicals, including inorganic fertilizer and pesticides, and advanced crop breeding. These developments have had important implications on SOM. The replacement of the horse by the tractor, together with a shift toward grain-fed livestock production, sharply reduced the need for forage-producing areas. With the availability of inorganic fertilizers, agriculture moved away from its emphasis on organic matter management as the key to maintaining soil fertility — consequently the use of legumes and green manures to provide nutrients to the crop declined. In Europe and North America, farming trends were toward monocultures or simpler rotation dominated by grain production, reduced ley acreages, residue burning to reduce disease and promote clean tillage, and increases in the number and intensity of tillage operations.[6] These developments were generally detrimental to the maintenance of SOM However, in areas which had historically been farmed for cash grain production, as in much of the North American prairies, increased productivity from fertilizers and improved crop varieties and the introduction of combine harvesters increased crop residue inputs, partially offsetting the negative effects of increased tillage intensity.[13]

While the new agriculture was able to produce unprecedented gains in agricultural productivity, there were early concerns that continuous fertilizer use and minimum residue return would lead to organic matter depletion and deterioration in soil tilth and quality. In this context, a number of field experiments investigating the balance of organic matter in soils were established in the 1950s and 1960s.[14–17] This renewed interest in SOM has continued to intensify to the present day and organic matter management is a major consideration in efforts to develop sustainable farming systems that minimize soil erosion and nutrient leakage and produce high-quality products.

The role of agricultural soils in the production and consumption of greenhouse trace gases is of more recent scientific interest.[18–21] While current contributions of land use to atmospheric CO_2 increase (approximately 25%[22]) are mainly from tropical regions, the rise in CO_2 during the 19th and early 20th centuries was largely associated with the rapid expansion of temperate zone agriculture. As much as 110 Pg (10^{15} g) of C may have been released from temperate zone ecosystems, contributing substantially to increased CO_2 prior to the mid-1900s.[23] Currently, the C balance in temperate agricultural soils appears to have stabilized[24], but there is considerable interest in evaluating the potential for these soils to regain some of their lost C and help ameliorate the continued increase in atmospheric CO_2.[24–26] A thorough knowledge of how soil C responds to various management practices is essential for these assessments. A prime source of this information is long-term field experiments of the kind described in this volume.

II. A CONCEPTUAL FRAMEWORK FOR ANALYZING MANAGEMENT EFFECTS ON SOIL C

A number of excellent reviews have been written about organic matter in agriculture soils and its response to management (e.g., References 27 to 31). Our purpose in this review is to organize knowledge and experimental results according to a systems framework where the focus will be on management factors as *process controls* on inputs and outputs of C from the soil.

A. PROCESSES DETERMINING SOIL C BALANCE

There is a tremendous store of empirical knowledge about the influence of management on SOM, and the practices which promote SOM formation and maintenance are well known. These practices include grass and legume production (in rotation or as permanent pasture), manure application, elimination of bare fallow, increased residue return, and reduced tillage. However, agricultural management is seldom, if ever, dictated by a primary objective of increasing SOM. For a given management system, the combination of tillage, cropping, fertilization, and manuring practices used is likely to have both positive and negative effects on SOM. Moreover, management effects on organic matter will vary for different soil types, climatic zones, and past management histories. Therefore, it is necessary to examine the fundamental processes which determine organic matter formation and decomposition and then analyze how specific management practices affect these processes.

In the simplest terms, the level of soil organic carbon in a soil will be governed by the difference between inputs of organic matter and outputs through mineralization, erosion, and leaching. Erosion can significantly affect the SOM content at a specific location, through the physical removal and transport of particulate organic matter. However, the extent to which erosion impacts the balance of C and other nutrients within the larger landscape will depend on the depositional pattern and subsequent fate of the eroded material. Ignoring for the moment the influence of soil erosion, the balance of soil carbon (the dominant constituent of SOM) is depicted in Figure 1.

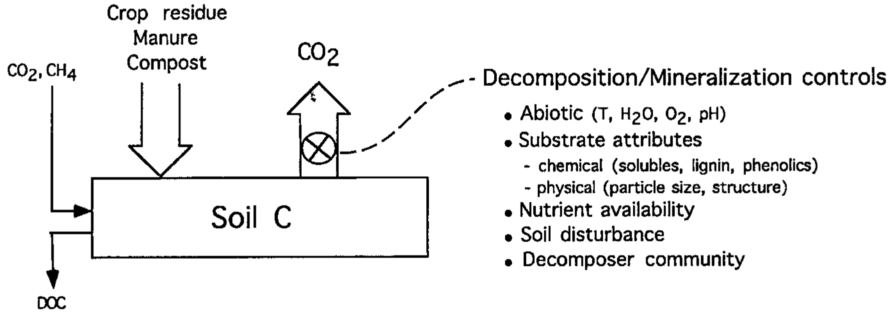

Figure 1 Inputs and outputs of C from organic matter in soils. The main controls on decomposition are shown as regulating CO_2 evolution by soil heterotrophs. (DOC = dissolved organic C).

The input of organic C to the soil consists of crop residues (including roots), animal manure, compost, and in some cases industrial-derived products in the form of sewage sludge and other wastes. Small amounts of carbon (as CO_2) are also incorporated in the soil by autotrophic microorganisms. Losses of C occur through the decomposition and mineralization of organic compounds by soil heterotrophs with CO_2 being the dominant product. Under reducing conditions (e.g., flooded soils), significant amounts of CH_4 and other hydrocarbons may be produced but in most well-drained agricultural soils there will be a net consumption of these gaseous compounds.[19] Carbon-containing compounds may also be leached from the soil profile as dissolved organic carbon (DOC). Except in acid soils, soil C losses as DOC are probably small.[32] However, there is relatively little information on this process in agricultural soil and some speculate that C losses via this pathway might be significant over the long term.[33,34]

The controls on decomposition processes are, in most respects, more complex and less easily manipulated by management than are inputs of organic matter. These controls include abiotic factors (soil temperature, water, aeration, pH), the physiochemical nature of the organic matter (i.e., chemical composition, structure, and particle size), its physical exposure to decomposers, the availability of mineral nutrients required for microbial growth and metabolism, and, finally, the nature and composition of the decomposer community itself (Figure 1).

B. INTERACTION OF MANAGEMENT CONTROLS

While the influence of individual control factors may be fairly well understood, the interactions and aggregate effects of multiple controls on decomposition and C inputs are more difficult to predict. Various components of agricultural management affect all of these process controls (Table 1). Moreover, a specific management practice (such as fertilization) may affect more than one control on decomposition or input and the multiple effects of a practice may act synergistically or in opposition.

There are many examples of interacting effects of specific management practices. Addition of N fertilizer might enhance the decomposability of crop residue (tending to reduce soil C) and at the same time increase crop residue production (tending to increase soil C). Mulching increases surface soil moisture and decreases soil temperature — however, the net effect on decomposition rates may be different for soils in a cool, wet climate as opposed to one that is warm and dry or for soils of different

Table 1 Summary of Management Practices Affecting Controls on Soil C Turnover

Process Control	Management Practice
C Inputs	Crop productivity (crop type, water and nutrient availability, pest control)
	Fallow frequency
	Residue return/removal
	Amendments (e.g., manure, compost)
	Cover crop production
Decomposition and mineralization	
Residue composition and particle size	Crop type, age, nutrient content
	Residue management (stubble retention, burned vs. unburned, chopping)
	Composting treatments
Temperature/moisture/aeration	Crop type and density (i.e., canopy shading)
	Tillage
	Mulching
	Irrigation
	Drainage
	Crop type (H_2O use efficiency)
Nutrient availability/soil reaction	Fertilization
	Liming
	Manure addition
	N-fixing crops and green manures
Soil disturbance/aggregation	Tillage
	Residue management
Decomposer community	Microorganism inoculation
	Earthworm addition

textures. An interaction between crop productivity and decomposition exists via the soil water balance, in that transpiration accounts for the bulk of water loss from most well-drained soils. Thus, management practices that increase productivity may tend to decrease soil moisture, thereby favoring a buildup of C through both increased C inputs and decreased decomposition.

To fully evaluate management influences on the soil C balance the processes must be analyzed within an ecosystem context.[35] A "causal loop" model of a number of soil properties and processes relating to the effects of soil tillage illustrates this point (Figure 2). The direct effects of tillage include the mixing of surface residues, roots, and other organic matter within the plow layer as well as the disturbance of the mineral soil matrix. These primary effects then spawn a series of secondary effects and feedbacks involving a multitude of physical, chemical, and biological processes and soil properties which are of consequence for the soil C balance. These effects vary temporally as well. For example, tillage could increase porosity and aeration of a soil initially, but lead to subsequent declines in these properties, relative to untilled soils, due to a decrease in aggregate stability.

Given the extreme complexity of the ecosystem interactions outlined above, one might ask whether it will ever be possible to make reliable quantitative predictions about the effects of a specific management system on C levels for a particular soil. Over the past several years, simulation models have begun to address some of the processes and interactions described here with a degree of success.[36–39] As more information is gathered, particularly results from long-term field studies such as those documented in this volume, and with accompanying advances in theory, the predictive ability of these models will continue to improve. Moreover, while we have focused considerable attention on the complexity of ecosystem responses to management, we would suggest that the effects of management are most predominant in two areas, (1) in controlling the amount and kind of organic matter returned to the soil and (2) in determining the degree of soil disturbance through tillage. Thus we will attempt to generalize the effects of management, focusing on tillage, organic matter addition, and residue management, crop rotation, and fertilization, based primarily on field studies conducted in temperate-zone agricultural soils. Before doing so, we will give an overview of the main crop-management zones in temperate North America and discuss constraints to agricultural production within the different regions. This will provide a context for subsequent discussion of how different management alternatives are likely to affect soil C levels in a particular region.

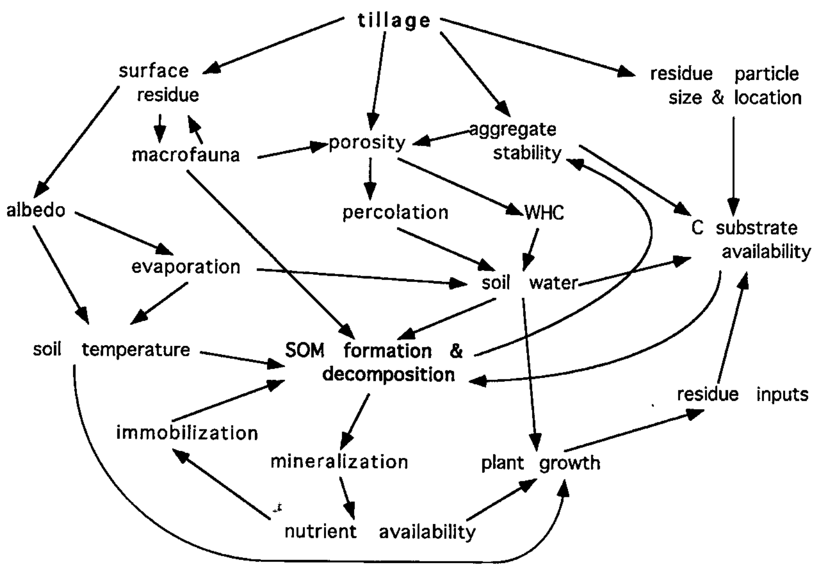

Figure 2 Causal loop model showing interactions and feedbacks between a management practice (i.e., tillage) and soil factors affecting organic C levels.

III. TEMPERATE CROPPING SYSTEMS AND MANAGEMENT CONSTRAINTS

North America, by virtue of its large size and the variety of its climate and soils, includes examples of the major types of cropping systems in current use in temperate regions worldwide. We recognize that there are crop species and management practices in other temperate regions which differ from those found in North America. However, we contend that in such cases reasonable analogs exist in North America for which the general principles of management and soil C interactions will be similar. Therefore, we will restrict our discussion to cropping systems and management constraints in U.S. and Canadian agriculture with the expectation that these can be compared to temperature zone agriculture globally.

Major land resource areas (MLRAs) for the principle crop growing regions of the U.S., as delineated by USDA/Soil Conservation Service,[40] are shown in Figure 3, with descriptions of major crops, average temperature and precipitation, dominant soil types, and land area coverage (Table 2). We have excluded MLRAs for which agriculture is of less importance, such as in the Rocky Mountain, Great Basin, and Pacific Coast regions of the West and the upper Northeast, which are dominated by forest or rangeland cover. We also neglect the MLRAs for central California and central and southern Florida. While these latter two regions are extremely important in terms of agricultural production, particularly of products for direct human consumption, they are more limited in area relative to most other crop-growing regions. In addition, their high diversity in crops and management practices makes it difficult to make meaningful generalizations on a regional basis.

The dominant control on the distribution of cropping systems is climate. As Jenny[41] pointed out, the Great Plains region of the central U.S. and Canada is characterized by regular, and roughly orthogonal, gradients of temperature and precipitation. Major cropping systems regions are arrayed according to these gradients (Figure 3). Moving eastward from the Rockies, precipitation is the major control of the transition from rangeland to cereal cropping with summer fallowing, to continuous cereal cropping, and then to row crop agriculture. The north-south temperature gradient also influences which systems are viable, by determining the length of the growing season and overwintering capacity of crops [e.g., accounting for the dominance of spring wheat in the Northern Great Plains (F) vs. winter wheat in the Central Great Plains (H)].

In the midwestern and eastern U.S., differences in precipitation are less important and the main determinant of large-scale cropping regions is temperature. In northern regions (e.g., Northern Lake States; K), cool moist conditions are most suited to perennial forage crops and short-season annuals. To the south are the main feed-grain-producing areas in the Corn Belt (M) and Appalachians and Ozarks (N), dominated by corn and soybean production. Farther south in the Atlantic and Gulf Slope and Coastal

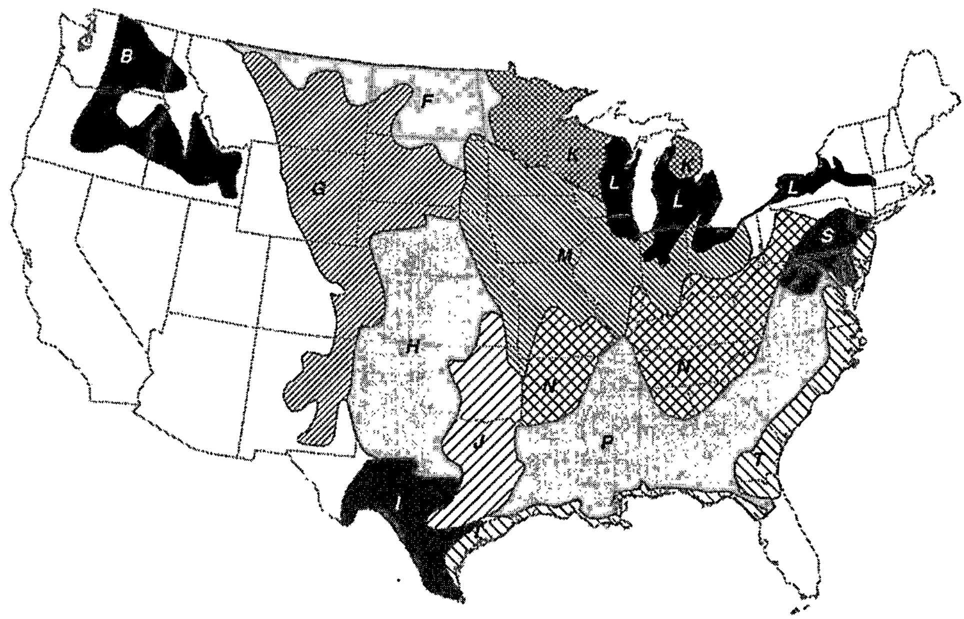

Figure 3 Distribution of the largest agriculturally important land areas in the continental U.S., based on major land resource area (MLRA) designations by the USDA, Soil Conservation Service.[40] See Table 2 for area codes and descriptions. (From USDA, Land Resource Regions and Major Land Resource Areas of the United States, Agriculture Handbook 296, 1981.)

regions (P,T) additional crops including cotton, tobacco, peanuts, etc., become important and the potential for double cropping and winter crops increases.

While not depicted in Figure 3, management systems in the major agricultural areas in Canada are broadly similar to those shown along the U.S.-Canadian border. For example, the spring wheat growing region (F) extends into southern Alberta, Saskatchewan, and Manitoba and the feed-grain and mixed cropping zones (M and L) extend into southern Ontario and Quebec. Further north, there is a decline in growing season length and in soil water deficit, resulting in progressively greater use of perennial forage crops, both in eastern and western Canada.

Soil C levels across the central U.S. (Figure 4) coincide to some degree with climate patterns,[42] although there is great variability locally associated with differences in parent material, topography, and drainage. In the central U.S., the precipitation gradient across the Great Plains influences productivity and rooting depth to a relatively greater degree than it does decomposition rates, giving a general trend of increasing soil C as precipitation increases west to east.[43] Within the semiarid and subhumid zones, SOM tends to increase south to north, due to lower temperatures (decreasing decomposition rates) and lower water deficits (enhancing productivity). The eastern U.S. lacks a strong regional gradient in precipitation and there is less of a regional gradient in soil C. Soil C tends to be greater in cooler regions and high C soils occur in floodplains and coastal areas due to the deposition of organic matter-rich illuvium and the presence of wetland ecosystems.

Climate and soil differences constrain management options and thereby determine which practices are most important in affecting soil C. For example, in the semi-arid regions of the Great Plains and Pacific Northwest, where wheat is the dominant crop, moisture limitations to productivity are of overriding concern. Therefore, fallow frequency and tillage intensity and their effects on water utilization are key management factors impacting soil C. The potential for increasing soil C levels will largely rest on the success in minimizing both fallow frequency and tillage (see Chapter 28). In the more mesic regions to the east, management controls on productivity levels (e.g., fertilization, crop type), as well as tillage practices and cover cropping, are key factors. In both cases, management practices that increase C inputs to soil and reduce decomposition rates associated with intensive tillage will promote maintenance and buildup of soil C.

Table 2 . Characteristics of Agriculturally Important MLRAs in the Continental United States

MLRA	Precipitation (mm)	MAT (°C)	Dominant Soils	Principle Land Use and Crops	Area (km²)
B. Northwest wheat and range region	250–570	7–10	Xerolls, Borolls, Ochrepts	Wheat-fallow; continuous grain and field peas where precipitation > 350 mm	240,000
F. Northern Great Plains spring wheat region	250–550	4–9	Borolls, Aquolls	Spring wheat-fallow Other spring grains, flax, hay	350,000
G. Western Great Plains range and irrigated region	275–600	7–16	Ustolls, Agrids	Range; irrigated feed grains; wheat-fallow on eastern edge	570,000
H. Central Great Plains winter wheat and range region	500–750	10–18	Ustolls	Winter wheat; irrigated corn, alfalfa and (in south) cotton	575,000
I. SW plateaus and plains range and cotton region	500–700	16–22	Argids, Othids (W) Ustalfs, Ustolls, Usterts (E)	Range; wheat and sorghum on favorable sites; irrigated cotton	175,000
J. SW prairies cotton and forage region	625–1150	15–22	Ustalfs, Ustolls, Usterts	Cotton, wheat, sorghum, other feed grains, hay	145,000
K. Northern Lake States forest and forage region	500–825	2–7	Boralfs	Forage and feed grains for dairy production	280,000
L. Lake States fruit, truck and dairy region	675–925	6–11	Udalfs, Boralfs	Dairy, corn, winter wheat, beans, sugar beets; fruit (on eastern edges of Great Lakes)	195,000
M. Central feed grains and livestock region (Corn Belt)	625–900	6–13	Udolls, Udalfs Aualfs, Aquolls	Corn, soybeans, oats, other field grains	725,000
N. East and Central farming and forest region (Appalachian and Ozarks)	1025–1275	9–17	Udalfs, Udults	Corn, soybeans, small grains, hay	610,000
P (&O). South Atlantic and Gulf slope (plus Mississippi Delta MLRA O)	1025–1525	16–20	Udults, Udalfs Aquents, Fluvents, Ochrepts in flood plains	Cotton, soybeans, small grains, corn; tobacco and peanuts locally	800,000
S. Northern Atlantic Slope diversified farming region	900–1275	8–14	Udalfs, Udults, Ochrepts	Truck crops, forage, soybean, feed grain	105,000
T. Atlantic and Gulf Coast lowland	1025–1525	13–21	Aquults, Aqualfs, Udults, Aquepts (E) Uderts, Aqualfs, Aquolls, Aquepts (W)	Rice (in west), corn, soybeans Tobacco, peanuts, sorghum (locally)	250,000

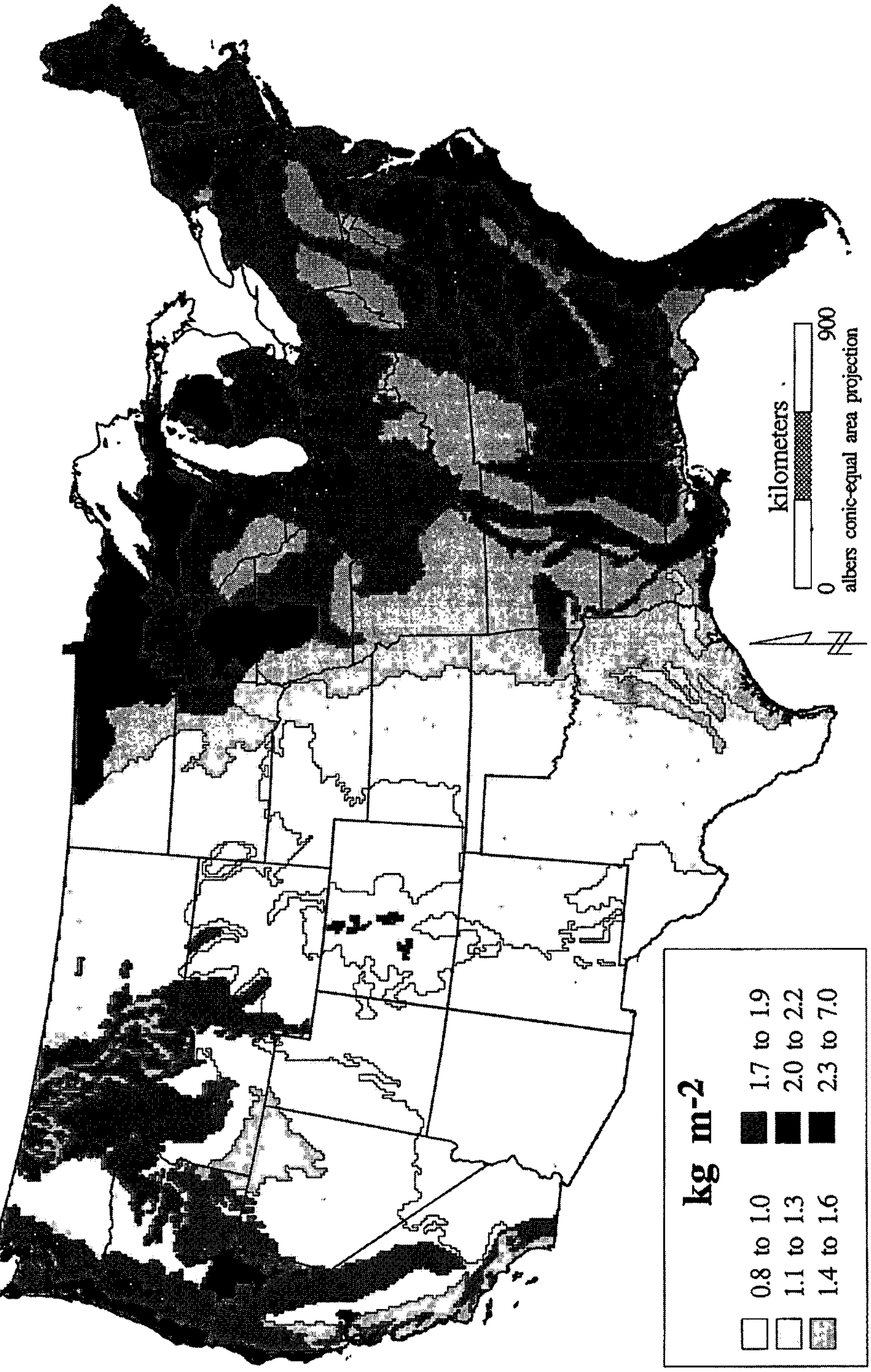

Figure 4 Spatial patterns of mean agricultural soil organic C for the continental U.S. (Figure courtesy of J. Kern, US-EPA, Corvallis.)

IV. MANAGEMENT EFFECTS ON SOIL C

A. CULTIVATION OF NATIVE SOILS

The most dramatic effects of agricultural land use on soil C are associated with the initial cultivation of native soils. Typically, C concentrations in the plow layer decline rapidly for several years following cultivation and eventually stabilize only after many years (Figure 5).

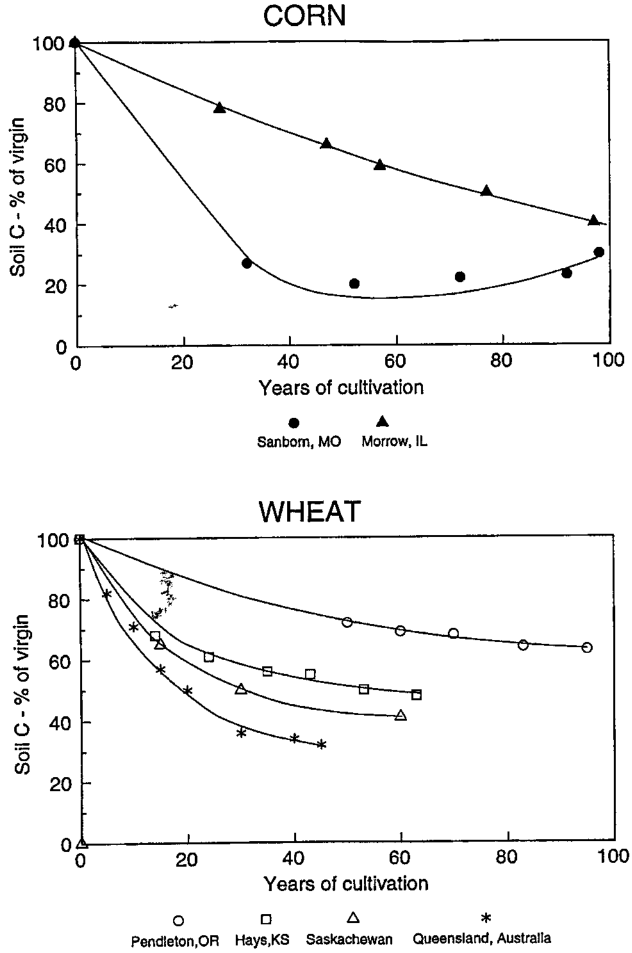

Figure 5 Declines in soil C with time since initial cultivation, grouped by corn- and wheat-dominated cropping systems. Data from Saskatchewan,[44] Hays, Kansas,[11] Pendleton, Oregon,[45] Queensland, Australia,[46,47] Morrow plots, Illinois,[48] and Sanborn plots, Missouri.[49]

The magnitude of change due to cultivation can vary substantially between locations. For example, Haas et al.[11] estimated decreases in C concentrations of 28 to 59% following 30 to 43 years of cropping for 11 sites in the Great Plains. Bowman et al.[50] reported a very high loss of C, 62% in the top 15 cm and 32% from the 15- to 30-cm depth, for a sandy soil in eastern Colorado after 60 years of cultivation. Mann[51] summarized much of the available literature of paired comparisons between virgin and cultivated soils in the U.S. and calculated regression estimates of C loss stratified by soil type and length of cultivation period. Estimates of maximum loss on a percent C basis in the upper 15 cm ranged from 11% for Psamments to 77% for Ustolls. However, *amounts* of C lost, calculated on a per area basis, were generally lower, as were estimates based on samples taken to 30 cm, i.e., below normal plow depth. She estimated average C losses for all soils to 30-cm depth to be 23% and concluded overall that *relative* C losses increased as a function of initial C content. Using a smaller but more detailed data set, Davidson and Ackerman[52] found that cultivation losses of surface soil C were generally between 20 and 40%. In contrast to the conclusion of Mann,[51] they found no effect of initial C content or soil texture on relative

C loss, where the data were calculated on a soil horizon basis rather than on the basis of fixed sampling depths. They, and others[53] point out that changes in bulk density or A horizon depth associated with cultivation can bias interpretations of C loss when comparing cultivated vs. uncultivated soils.

A number of factors may contribute to losses in soil C upon cultivation including reduced C inputs, physical soil disturbance, a more favorable decomposition environment, and increased soil erosion. The predominance of any one factor is highly site specific and thus broad generalizations are difficult. Furthermore, as management systems evolve and change, so does the soil C status relative to the original native condition. Specific effects of individual management practices are discussed later in the paper. In this section we are primarily concerned with the impacts of the initial disturbance of native soils.

The degree of change in C inputs depends on the production system which replaces the native vegetation. Even with harvest removal of grain, high input agricultural systems could return as much or more C to the soil as the native systems they replaced. Conversely, more extensive production systems including, for example, use of summer fallow, as well as extensive residue removal, may greatly reduce C return relative to native ecosystems. In addition, the distribution of C inputs may be altered; for example, lower proportions of C are added below ground in annual crops vs. perennial grassland.[54]

There are relatively few comparisons of native vs. cultivated ecosystems which specifically address differences in plant residue inputs. Buyanovsky et al.[55] made a detailed study of C budgets for winter wheat and native grassland on similar sites in Missouri. Although net primary production in winter wheat was about 10% higher than that in the native system, the amount of C allocated to SOM was 80% greater in the grassland. They found that decomposition rates of fresh residues were also higher for winter wheat, due to tillage disturbance and incorporation of residues and higher soil moisture contents during summer. Consequently, the grassland was able to maintain higher SOM levels due both to higher C inputs as well as slower residue decomposition rates compared with cultivated winter wheat. van Veen and Paul[56] compiled data for southern Saskatchewan and reported that residue production from grassland (2000 kg C ha^{-1} yr^{-1}) was greater than for corresponding wheat (1425 kg C ha^{-1} yr^{-1}) systems.

Cultivation invariably affects soil structure and conversion from grassland or pastures to cultivated land yields substantial reductions in aggregate stability within a few years.[57–61] The breakdown of stable macroaggregates is thought to promote decomposition of previously physically-protected organic matter through greater exposure to soil organisms and improved aeration.[62–64] Differences in cultivation response as a function of soil texture may be associated with the vulnerability of a soil to physical disturbance. Several authors have reported higher relative C losses following cultivation in coarse-textured compared with medium- and fine-textured soils.[65–68] In coarser-textured soils, the structural stability of the soil depends mainly on binding agents such as roots and fungal hyphae,[60] which are disrupted and rapidly decomposed upon disturbance. Higher clay contents promote organo-mineral complexes which may allow smaller aggregates to persist, protecting some of the physically stabilized SOM from decomposing following disturbance.[69]

Improved abiotic conditions for decomposition following cultivation could include more optimal temperature or moisture regimes, increased aeration, improved pH, and increased nutrient availability. In temperate regions, soil temperatures are below optimal for the microflora during a major portion of the year. The lower albedo of bare soil surfaces and higher incident radiation during spring and fall tend to increase soil temperatures in annual crops. Increases in soil moisture following conversion of grassland or forest to cultivated land could occur as a consequence of lower evapotranspiration rates, particularly with the practice of summer fallowing. Thus well-drained soils under cultivation are likely to have temperature and moisture regimes that are more favorable for decomposition. At the other extreme, drainage of wet soils improves aeration which also speeds decomposition. Changes in soil reaction and nutrient availability with cultivation are probably of less importance as *direct* controls on SOM levels in agricultural soils. However, nutrient and pH status have significant indirect influences on soil C turnover, primarily through effects on productivity and residue inputs, as discussed later.

Once native soils have been cultivated they are much more susceptible to erosion. Reduction in the C content of surface soils as a result of erosion is due both to the loss of topsoil and to a dilution effect from subsoil mixing. On a landscape basis, the net effect of erosion on C balance will depend on the deposition pattern of the eroded soil and changes in productivity and decomposition rates of the eroded soil. Depending on these factors, net soil C storage on a landscape basis could be either reduced or increased. If eroded soil is deposited in upland sites, decomposition rates of the C in the depositional soil may not be greatly altered. However, if soil is transported to basins or wetland areas, where decomposition rates are reduced, then net soil C storage on a landscape could conceivably be increased by erosion. Conversely, if productivity of the eroded soil is significantly reduced, net C storage in soil would be decreased due to decreased C inputs. However, if productivity was largely maintained (e.g., through the use of fertilizers) then subsoil mixed into the root zone through tillage could become enriched in organic matter and net soil C storage, minus erosional losses, could increase.

Most long-term field experiments were established on relatively level ground in order to minimize water erosion and soil variability. Nevertheless, several studies have shown that water erosion can be significant even with slight slopes and in many cases erosional losses by both water and wind are a confounding factor in estimating C turnover from long-term studies. For the Sanborn plots, Gantzer et al.[70] calculated that topsoil thickness had been reduced by 56% under continuous corn and by 30% under corn rotated with oats, wheat, and perennial crops, compared with permanent timothy grass. In long-term plots at Wooster, Ohio, Dick et al.[71] estimated that conventionally tilled plots lost about 3.7 cm more soil than no-tilled plots over 18 years, an amount equivalent to about 500 g C m^{-2}. Slater and Carleton[72] showed that decreases in soil C content were closely correlated to cumulative soil loss for corn plots and corn rotated with cereals and hay, in two sets of erosion plots in Iowa. They found that C losses from erosion *exceeded* that accounted for by reduced C content of the top soil. From this it can be inferred that either SOM formation exceeded decomposition losses — the difference making up the additional C lost to erosion — or that subsoil mixed into the surface horizon was sufficiently high in C to dampen the apparent losses due to erosion. In a toposequence of soils under cultivation for varying lengths of time, Gregorich and Anderson[73] quantified C losses due to erosion vs. C loss through mineralization, for Boroll soils on the Canadian prairies. They found that, for upslope positions, mineralization accounted for most of the carbon loss (70%) during the first years following cultivation but that erosion accounted for 70 to 75% of C loss for the two soils that had been cultivated more than 50 years. Carbon loss in the lower slope (depositional) area was more than double the C lost by erosion upslope, suggesting that the decomposition rate of the deposited material was at least as high as it would have been if it had remained in place and not been eroded.

B. CARBON INPUTS AND RESIDUE MANAGEMENT

One side of the soil C balance equation is the amount of C entering the soil, the other side being the amount decomposed. Plant residues are the major source of C inputs in all terrestrial ecosystems. In agricultural systems an additional "source" of organic matter is available in the form of manure, sewage sludge, and other organic by-products. However, depending on the scale considered, these inputs might be more properly viewed as a redistribution, since animal and human waste, food processing waste, etc., originate mainly from harvested plants.

For a given climatic region and soil type, the rate of C input is an important factor determining the amount of C which can be maintained in the soil. This fact has been recognized for some time and numerous calculations have been made of the amount of residue return needed to maintain organic matter levels at a particular site.[15,74–77] Residue inputs are under a high degree of control by the farmer, via crop selection, productivity levels (as influenced by fertilizers), residue management, and use of manure and other external additions. Thus, in our subsequent evaluations, the role of specific management practices (e.g., crop rotation, fertilizer use, etc.) on C inputs will be an important focus.

If organic matter decomposition is viewed as a series of first-order processes (i.e., constant *fractions* of organic matter decomposed per unit time) as most current theories espouse, then it is easily seen that the amount of SOM that can be potentially maintained in soil (i.e., the steady-state level, C_t^*) is directly proportional to the rate of C inputs (I). This holds true regardless of the number of different fractions considered as comprising SOM[47,78] as shown in the equation below. The rate of change of total C can be expressed as a function of C inputs and the specific decomposition rate (k) of soil C fractions, i.e.,

$$dC_t/dt = d(C_1 + C_2 + \ldots + C_n)/dt = I - k_1C_1 - k_2C_2 - \ldots - k_nC_n \quad (1)$$

Since at steady-state each individual pool would make up a constant fraction (f) of total C ($C_1 = f_1C_t^*$), then,

$$I = k_1(f_1C_t) + k_2(f_2C_t) + \ldots + f_n(k_nC_t) ,$$

$$I = (k_1f_1 + k_2f_2 + \ldots + k_nf_n)\ C_t^*$$

$$I = k_tC_t^* \quad (2)$$

A number of long-term field experiments, where residue additions have been carefully controlled, support the theoretical proportionality between inputs and soil C levels (Figure 6). While the soil C data shown here do not necessarily reflect differences at equilibrium, the linearity between differences in soil C levels and C input rates (normalized as mean annual C change over the experimental period) conform to the predictions of the multiple first-order model. The degree of change in soil C (i.e., given by the slope coefficient) depends on climatic and edaphic factors affecting decomposition rates at a particular site. Also, since the instantaneous rate of change of SOM decreases over time following a change in inputs, short-duration experiments would be expected to show higher *mean* changes in soil C, as appears to be the case for experiments at Lind, WA (17 y) and Culbertson, MT (7 y).

Most other studies of residue additions or removals generally show similar effects on organic matter,[77,81–84] although the magnitude of the response varies considerably depending on the length of the experiment, climate and soil type, and management system. Short- and medium-term changes in SOM are often difficult to detect against background soil variability. Saffigna et al.[85] used initial values of soil C as a covariate in analyzing effects of sorghum residue retention and showed significantly higher soil C levels, compared to where residues were removed after only 6 years.

A few studies have shown surprising little response of soil C to differences in carbon inputs. Referring back to Equation 2, it is unreasonable that equilibrium SOM can increase indefinitely with ever-increasing C inputs (plus there are practical limits to the amount of residue which can be added to soil). This implies an upper limit to the amount of C which can be sequestered in mineral soils, independent of input rate. This is suggested by the C balance analyses by Campbell et al.[86] for a high organic matter soil at Melfort, Saskatchewan, which showed no effect of varying C inputs on SOM levels (Figure 7). One hypothesis is that there is a maximum amount of C which can be stabilized in organomineral complexes that are resistant to decomposition and that, once this capacity is saturated, additional residues remain accessible to rapid microbial decomposition and add little to the total soil C storage.

Residue return to the soil can be reduced by burning. Burning of crop residues, to control diseases and to remove impediments to tillage or furrow irrigation, has been practiced in many cereal-growing regions. Burning over many years has been observed to decrease soil C levels,[82,87–89] although in some instances the effects appear to be less than would be expected considering the amount of C volatilized during burning.[76,90] The creation of more resistant C fractions (e.g., charcoal) by burning and variation in the amount of residue remaining after burning (25 to 70% for wheat straw[88]) may account for differences in soil C response.[91]

Of the commonly used organic amendments, farmyard manure is the most recognized in its ability to maintain and build SOM as shown in numerous long-term field experiments.[38,80,83,92–99] Having passed through the digestive tracts of animals, manure is enriched in more refractory compounds and is therefore stabilized to a relatively higher degree than fresh plant residues. Thus, effects of manure applications on SOM content can persist for many years after applications have ceased.[83,96,100] Particle-size fractionation studies show that manure applications increase the relative amounts of C in clay and silt size fractions, which have longer turnover times compared to the sand fraction.[101,102]

The effects of green manures on soil C are more variable than those for farmyard manure. In their review, MacRae and Mehuys[103] cite nine experiments, of which five showed net increases, two showed decreases, and two showed no change in SOM over the study period. However, in the two studies which showed no change (in the Woburn plots, U.K.), the original paper by Chater and Gasser[92] reported that organic matter declined in the absence of green manuring (i.e., with straw return alone) and that green manure was as effective as farmyard manure in *maintaining* soil C levels. In contrast, green manure crops in several long-term plots in the Central Great Plains were generally not effective at reducing C or N losses compared with rotations with only cereals.[11,104] In these studies, low yields of green manure crops and the negative effects of their water use on following grain crops did not increase (or may have decreased) C inputs compared with rotations with cereals only (e.g., Krall et al.[104] cite several years in which green manure crops failed). Under these conditions soil C contents would not be expected to increase.

The effect of different kinds of residue (including manure) on C stabilization efficiency has long been of interest to farmers and soil scientists. The conventional wisdom has been that animal manures and composts are more effective at building SOM than harvest residue, which in turn is more effective than fresh plant material such as green manures. However, it has been pointed out that, if the stabilization efficiency of manure-derived C is based on the amount of original plant material it represents, then the humification efficiency for manure is not necessarily higher than for the original plant material.[28,83] More important perhaps is the degree to which stabilization efficiency can be related to general characteristics

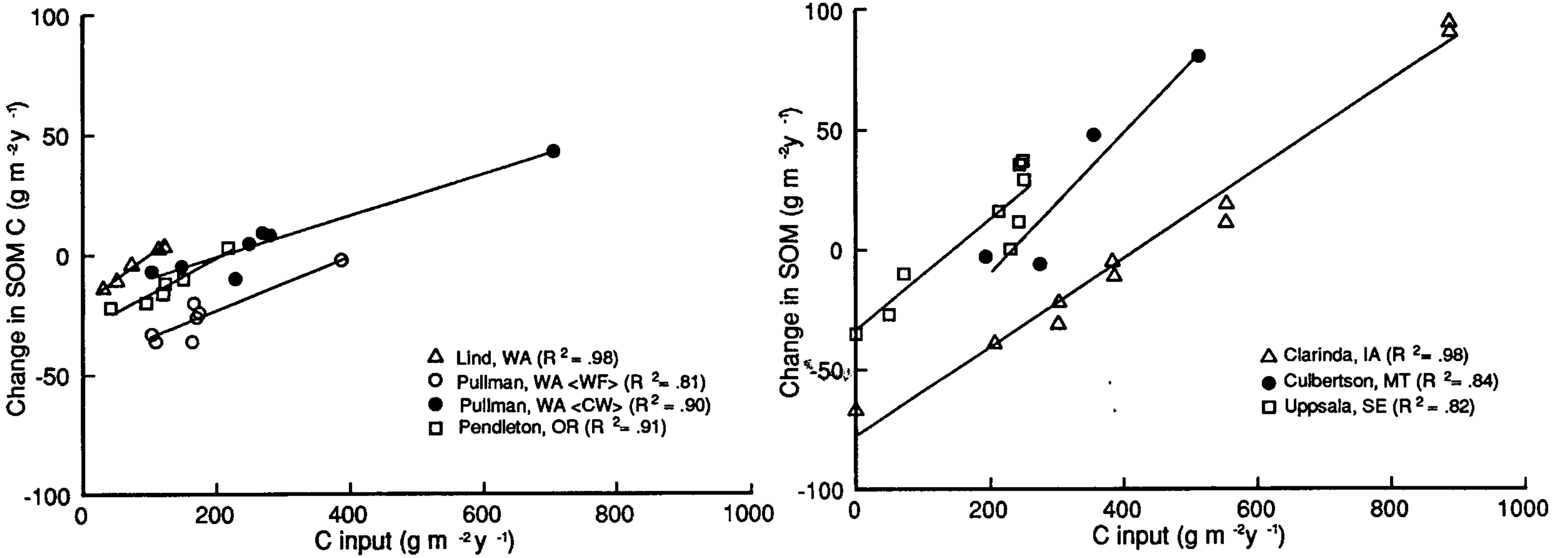

Figure 6 Linearity between soil organic C levels and C inputs from residues. Annual changes in soil C are averaged over the duration of the experiment. Data from Black,[79] Horner et al.,[80] Larson et al.,[15] Paustian et al.,[38] and Rasmussen et al.[76] (From Paustian K., Robertson, G.P., and Elliott, E.T., *Soil Management and Greenhouse Effect*, Lal, R., Kimble, J., Levine, E., and Stewart, B.A., Eds., *Advances in Soil Science*, Lewis Publishers, Boca Raton, FL, 1995. With permission.)

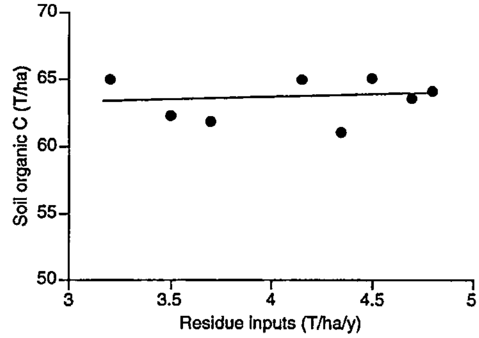

Figure 7 Soil C levels as a function of residue inputs, showing no response to input levels, for a 30-year-old experiment at Melfort, Saskatchewan. (Modified from Campbell, C.A., Bowren, K.E., Schnitzer, M., Zentner, R.P., and Townley-Smith, L., *Can. J. Soil Sci.*, 71, 377, 1991c.)

of residues. Paustian et al.[38] found that differences in soil C levels for various organic amendments in field plots in Sweden were well described by the lignin contents of the residues (Figure 8). Similarly, small plot experiments in Canada showed significant influences of residue quality on changes in soil C levels, where C input rates were held constant (Figure 8). The lignin and N content of residues also helped account for differences in SOM in long-term plots receiving straw, pea vine, or manure residues at Pendleton, Oregon.[39]

In addition to their role as the primary source of C inputs, crop residues and the way in which they are managed have significant impacts on soil physical properties including bulk density, water infiltration, pore size distribution, and aggregate stability.[106,107] With respect to soil C maintenance, residue effects on aggregation and aggregate stability are of particular importance since aggregation is viewed as a key mechanism in promoting C stabilization.[63,69,108] Retention of residues generally increases the number and stability of soil aggregates.[107,109–111] Morachan et al.[112] found that aggregate stability increased in proportion to residue addition rates. Smika and Greb[113] reported that the proportion of aggregates greater than 0.84 mm (classified as nonerodible by wind) increased with increasing rates of wheat straw retention. Halstead and Sowden[114] reported greater aggregate stabilities in all residue amendments compared with unamended soil and found that stability was greatest with straw, manure, or sludge amendments and less for alfalfa, deciduous leaves, or ryegrass litter. By enhancing aggregate stability, increasing residue inputs may have a synergistic effect by providing more raw material for humification as well as increasing the stabilization potential of that material through increased aggregation.[106]

C. TILLAGE

The idea of tillage is fundamental to most people's view of agriculture and the invention of the plow and its subsequent refinement over several thousand years has been a major force in human development. Jethro Tull, whose writings and inventions were highly influential in the preindustrial European agricultural revolution, energetically promoted the benefits of intensive tillage as a means of breaking down the soil into minute particles which could then be absorbed by plants.[3] Although his theory of plant nutrition was subsequently refuted, Tull's prescription contained an element of truth in that part of the effectiveness of intensive tillage is to speed the release of nutrients contained in SOM. However, over the long term, intensive tillage has caused or contributed to soil degradation in many regions. Reducing erosion and organic matter losses in cultivated soils has been the primary reason for the development of less-intensive tillage practices.[115–117]

Tillage affects the processes determining soil C balance in two fundamental ways, (1) through the physical disturbance and mixing of soil and the exposure of soil aggregates to disruptive forces and (2) through controlling the incorporation and distribution of plant residues in the soil. Important secondary effects of tillage on the soil microclimate include the influence of surface residue coverage on soil temperature, water interception and infiltration, and the effects of tillage-induced changes in porosity and soil structure on soil aeration and water relations. Conventional tillage, based on the moldboard plow (CT) and no-till (NT), represent opposite ends of the tillage spectrum and would be expected to show the greatest differences in soil C response. Therefore, our discussion will largely focus on comparisons of these two tillage systems.

The degree of soil disturbance caused by tillage is difficult to define and quantify but a commonly used measure is aggregate stability. By increasing the effective soil surface area and continually exposing new soil to wetting/drying and freeze/thaw cycles at the surface, tillage makes aggregates more susceptible to disruption and physically protected interaggregate organic material becomes more available for