u	Wind velocity ($\mathrm{m\,s^{-1}}$)
W	Soil water (mm)
z_e	Depth of soil contributing to evaporation (m)
z_h	Height of air temperature measurement (m)
z_m	Height of wind velocity measurement (m)
z_{oh}	Roughness length for heat (m)
z_{om}	Roughness length for momentum (m)
z_r	Rooting depth (m)

See also: **Evapotranspiration**; **Irrigation**: Methods; **Plant–Soil–Water Relations**

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CROP-RESIDUE MANAGEMENT

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Introduction

Soils, along with water, air and sun, are the major resources that sustain our food supply and terrestrial ecosystems. Soil organic matter is one of the primary contributors to soil quality. Crop residues are precursors to soil organic matter (SOM). The stems, leaves, chaff and husks that remain in the fields after crops are harvested for grain, seed or fiber play a critical role in soil quality and environmental issues since they are primary inputs of elemental carbon (C) into soil systems (**Figure 1**). Crop residues have been referred to as 'wastes' but as a natural and valuable resource are also considered to be 'potential black gold.' The negative connotation of 'residues' may refer to the remains after a part is taken or something leftover or useless. On the contrary, crop residues offer a large, but finite potential mechanism for C sequestration and nutrient cycling.

Crop residue management (CRM) is a widely-used cropland conservation practice for wind and water erosion control. Crop residue provides significant quantities of nutrients for crop production. In addition to affecting soil physical, chemical and biological functions and properties, crop residues can also affect water movement, infiltration, runoff and quality. However, the decomposition of crop residues can have both positive and negative effects on crop production and the environment. The presence of crop residues on the surface generally results in wetter and cooler conditions, thus favoring disease and pests, and also provides pathogens with an additional source of energy to multiply. Agricultural managers aim to increase the positive environmental effects of CRM since each practice has drawbacks. Ideally, improved management practices should enhance crop yields and have minimal adverse effects on the environment.

Crop management recommendations for maximum residue production require basic scientific research information regarding site-specific soils, crops and climate. Soil conservation and CRM research covers many aspects including the factors affecting residue decomposition, effects on erosion control, nutrient cycling and plant availability, disease control problems, weed control problems, alternate uses of excess residue, selection of plant varieties for conservation tillage systems, machinery requirements and control of the soil–water–temperature regime.

Conservation, Carbon Cycle, Soil Organic Matter and Carbon Sinks

Conservation of soil resources requires proper management of crop residues. The primary limiting factor for microbial growth in most soils is the C energy source. An abundance of C and other nutrients are returned to the soil through decomposition of crop evapotranspiration is assumed relative to a crop canopy such as grass but with constant crop characteristics. The hypotheses on which this approach is based are discussed relative to crop surface and aerodynamic resistances to heat and vapor fluxes. The crop evapotranspiration is defined using crop coefficients applied to the reference evapotranspiration, which reflect the canopy differences between the crop and the reference crop. Both time-averaged and dual-crop coefficients are explained, the first when the coefficients relative to crop transpiration and evaporation from the soil are summed and averaged for the crop-stage periods, the latter when a daily calculation of transpiration and evaporation coefficients is adopted. Finally, essential information on the soil water balance to estimate crop irrigation requirements is provided.

List of Technical Nomenclature

β	Bowen ratio (dimensionless)
γ	Psychrometric constant (kPa°C^{-1})
Δ	Slope of the saturation vapor pressure–temperature function (kPa°C^{-1})
ΔS	Change in soil-water storage (mm)
θ	Soil-water content (mm mm^{-1})
θ_{FC}	Soil-water content at field capacity (mm mm^{-1})
θ_{WP}	Soil-water content at wilting point (mm mm^{-1})
λ	Latent heat of vaporization (kJ kg^{-1})
ρ	Air density (kg m^{-3})
c_p	Specific heat of dry air (kJ kg^{-1} °C^{-1})
D_a	Average total water available for evaporation (mm)
D_e	Evaporated water (mm)
DP	Deep percolation (mm)
d	Zero-plane displacement height (m)
E_s	Evaporation from bare soil (mm day^{-1})
E_{so}	Potential rate of soil evaporation (mm day^{-1})
ET	Evapotranspiration (mm s^{-1})
$\mathrm{ET_c}$	Crop evapotranspiration (mm day^{-1})
$\mathrm{ET_o}$	Reference evapotranspiration (mm day^{-1})
$e_s - e_a$	Vapor pressure deficit (VPD) (kPa)
f_c	Fraction of ground covered by vegetation (dimensionless)
f_{ew}	Fraction of exposed wetted soil (dimensionless)
f_w	Fraction of wetted soil fraction (dimensionless)
GIWR	Gross irrigation water requirement (mm)
GW	Groundwater contribution (mm)
h	Crop height (m)
I	Total irrigation depth (mm)
IWR	Irrigation water requirement (mm)
I_w	Infiltration depth from irrigation (mm)
K_c	Crop coefficient (dimensionless)
K_{cb}	Basal crop coefficient (dimensionless)
K_e	Soil-water evaporation coefficient (dimensionless)
K_r	Evaporation reduction coefficient (dimensionless)
K_s	Stress-reduction coefficient (dimensionless)
k	Von Karman constant (dimensionless)
LAI	Leaf area index (dimensionless)
LR	Leaching requirement (mm)
MAD	Management-allowed depletion (dimensionless)
n_w	Number of wetting events (dimensionless)
P	Precipitation (mm)
P_n	Net precipitation (mm)
p	Depletion fraction for no stress (dimensionless)
REW	Readily evaporable water (mm)
RH	Relative humidity (%)
RO	Runoff (mm)
$R_n - G$	Net balance of energy at the surface (kJ m^{-2} s^{-1})
r_a	Aerodynamic resistance (s m^{-1})
r_l	Bulk stomatal resistance (s m^{-1})
r_s	Bulk surface resistance (s m^{-1})
TEW	Total evaporable water (mm)
T	Mean daily temperature (°C)

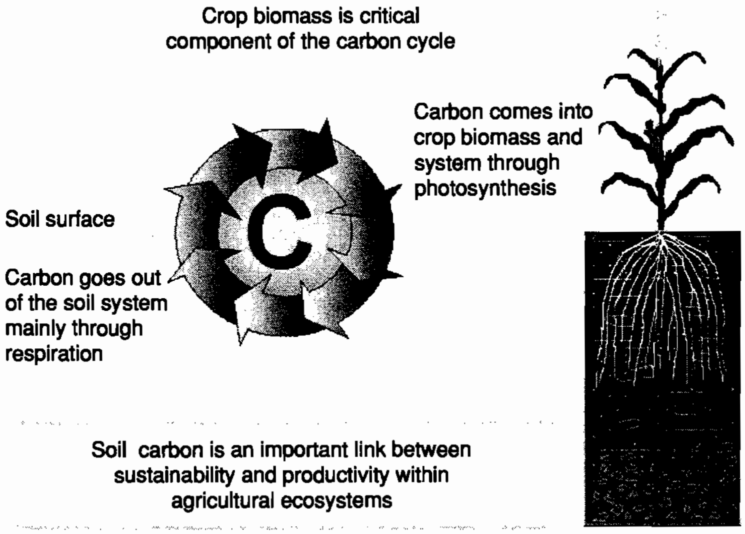

Figure 1 Schematic representing the role of crop biomass in the agricultural ecosystems carbon cycle.

residues and biological nutrient cycling. Since organic matter (OM) is known to maintain soil aggregate stability, the addition of crop residues often improves soil structure and aggregation. Crop residues and tillage management can also affect the leaching of the nutrients, which may pollute the groundwater or surface waters. Crop residue influences soil temperature primarily by insulating the soil surface from the sun's radiant energy. Studies have shown that soils high in SOM retain more moisture, especially when residues are retained on the soil surface as compared to when they are incorporated.

The recent interest in global climate change has prompted many to value C sources and sinks in agroecosystems. Soil C pools and fluxes in agroecosystems are influenced by a number of factors including amount and type of plant residue, temperature and precipitation and soil texture, pH and drainage. Carbon sequestration or storage in terrestrial ecosystems can be defined as the net removal of carbon dioxide (CO_2) from the atmosphere by crop photosynthesis into stable, long-lived pools of C. The soil organic carbon (SOC) pool is estimated to compose about two-thirds of the terrestrial biosphere C pool. Soil organic C storage in cropland soils is determined by tillage systems and the amount and placement of the crop residue. As grain and biomass yields increase and less intensive tillage systems are employed, farmers should gradually develop an enhanced C sink.

Crop Residues and Nutrient Cycling

The annual cycling of plant nutrients in the plant–soil ecosystem is essential to maintaining a productive agricultural system. The management of crop residues has important implications for the total

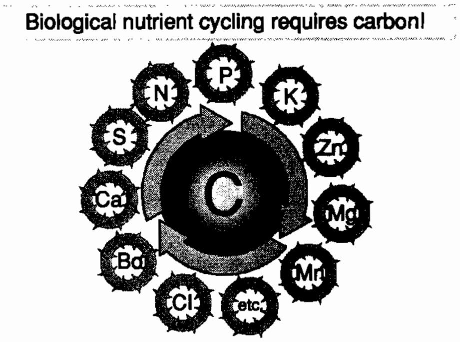

Figure 2 Soil carbon plays a critical role in biological nutrient cycling.

amounts of nutrients removed from and returned to the soil. Soil organic matter also improves the dynamics and bio-availability of main plant nutrient elements. The soil, water, and air, which are in contact with plants, contain various inorganic chemicals necessary for plant growth. Soil organic matter is the main determinant of biological activity because it is the primary energy source. The amount, diversity and activity of soil fauna and microorganisms are directly related to SOM content and quality.

Organic matter and the biological activity that it generates have a major influence on the physical and chemical properties of the soils. Each plant nutrient has its own C-dependent cycle (**Figure 2**) that controls its availability to the next generation of plants. Carbon compounds in the residue are the 'fuel' or energy sources for the soil microbes and fauna responsible for biological recycling of these inorganic plant nutrients. During microbial decomposition of crop residues, chemical elements are released into the immediate environment that may be utilized by living plants or other organisms. This constitutes the basic framework of biological nutrient cycling in agricultural production systems. Carbon-enriched crop biomass becomes the primary food source for soil microorganisms and fauna and as a result 'nurtures' nutrient cycling.

Plant availability of nutrients (nitrogen (N), phosphorus (P), and potassium (K)) in crop residues is regulated largely by soil water, soil temperature, other soil physical and chemical properties, and soil and crop management practices. For N, activity of soil microorganisms is usually most important in determining the cycling and potential availability from crop residues; for P, both microbial activity and soil mineralogy are involved; and for K, mineralogy and soil water movement are important parameters. Management practices such as fertilization and the amounts of residue remaining after harvest determine the extent of cycling and plant availability of nutrients from crop residues. The shift from conventional to conservation tillage systems necessitates new research to determine the rate of cycling and plant nutrient availability.

Crop residues can be managed for increased OM levels, thereby sequestering C. The position and quantity of crop residue as well as N fertilization have variable influences on SOM. Several studies have indicated that when more crop residues were on or near the surface, as in no-till or reduced tillage systems, SOM content near the surface was increased, but when incorporated to depth by moldboard plow tillage, the quantity of crop residue had little or no influence on SOM. The physical incorporation and mixing of residue maximize soil-residue contact and result in rapid decomposition and C loss as CO_2.

The C:N ratio of the residue, an important key in soil management, also varies. Crop biomass is generally 40–50% C, but the nitrogen (N) content varies considerably within and among species. Thus, an adequate supply of N may be required to build SOM for crops with a high C:N ratio since C and N and their proportionality (i.e., C:N ratio) is relatively constant across a range of agricultural soils at about 10:1. For example, wheat straw has a C:N ratio around 90:1 and will require N addition or C loss to decompose to the soil equilibrium value of 10:1. Thus, soil C sequestration may be reduced when C and N inputs of the residue are out of balance.

Factors Controlling Residue Decomposition and Soil Quality

Soil microorganisms play a major role in the synthesis and degradation of crop residues into SOM. The decomposition rates of OM and crop residue depend primarily on chemical composition and on factors that affect the soil environment. Factors having the greatest effect on microbial growth and activity will have the greatest potential for altering the rate of residue decomposition in soil.

Soil factors that typically influence residue decomposition most include water, temperature, pH, aeration or oxygen supply and available nutrients. Residue factors include chemical composition of the residue, C:N ratio, age of plant material, particle size and the indigenous microflora. Additional factors that must be considered are the residue water content and the method of residue application to the soil (i.e., mixed with the soil, layered or banded in soil or left on the soil surface). Many of these factors are not independent and a change in one may affect a change in others.

Plant residue decomposition rates generally increase when residues are accessible to soil microbes. Many studies indicate that burying residues in soil increases the decomposition rate compared to placing residues on the soil surface. The effect of placement decreases with time. Thus, tillage maximizes residue–soil contact and enhances decomposition. Soil enzyme activities also respond to tillage practices. Crop residues and tillage have been reported to significantly and rapidly alter the composition, distribution and activity of the soil enzymes. Although straw amendments also contain some enzymes, the increase in activity in soils with organic residues most likely results from the stimulation of microbial and fungal activity rather than the direct addition of enzymes found in organic residues. Soil macroorganisms, such as earthworms, also play a role in crop residue decomposition. The nutritional quality and C:N ratios of plant material appear to be important factors that influence earthworm population.

Soil organic matter and humic substances exert physical, chemical and biological effects on soil quality by serving as soil conditioners, nutrient sources and substrates for microorganisms. Humic substances contribute to soil structure by acting as binding agents in the formation of soil aggregates. As a result, a stable soil structure ensures satisfactory drainage and aeration, provides protection against erosion and enhances soil properties. Humic substances are sources of nutrients that are essential for plant growth. These substances, which can be derived from crop biomass, impact soil quality and fertility and contribute to the vital role of SOM.

Crop Residues: Social and Environmental Benefits

Many of the social and environmental benefits of carbon cycled from crop residues are subtle and often difficult to detect. Integrating the numerous

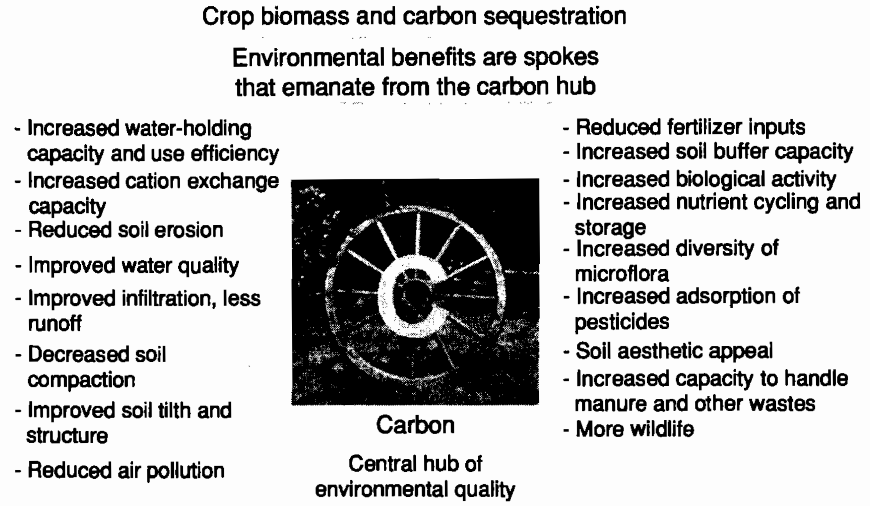

Figure 3 An environmental quality wheel illustrates results from numerous environmental benefits emanating from the carbon hub.

'small' benefits from C generated from crop residues yields important environmental benefits. Soil C from crop residues may be considered analogous to the central hub of a wheel (Figure 3). The spokes of the wheel represent incremental links to or benefits from soil C that lead to environmental improvement. Each of the secondary benefits that emanate from soil C contributes to environmental enhancement through improved soil C management. Crop biomass provides the C that becomes the supporting spokes of the environmental sustainability wheel.

Social benefits of agricultural residue management may include many off-site consequences of adopting new farm technologies and improving cultural practices. Reductions in runoff and soil erosion from cropland and rangeland enhance the functioning of streams, rivers and lakes through reduced flooding and sedimentation. The useful life of public facilities, a benefit to society, may be extended through improved water quality. Other important off-site benefits related to wind erosion have a direct impact on air quality. Air quality is primarily stressed in areas of industrial pollution and concentrated populations, but is often overlooked in rural areas as soil erosion by wind-driven particles. Additional benefits of CRM include providing both protective cover and a source of food for wild game.

Crop Residues, Research and Global Change

Agricultural crop residues and their proper management can also play an important role in helping society cope with increased greenhouse gas emissions from the burning of fossil fuels. The agricultural sector has a large capacity for removing CO_2 from the atmosphere and abating the emission of its own greenhouse gases. Croplands have the potential to offset a very significant portion of greenhouse gas emissions, but questions about climate change impacts on crop residue decomposition research need to be addressed. Specifically: (1) To what extent does climate change affect diversity of plant species and soil biota and residue decomposition processes? (2) What methods of decomposition management should be utilized to control C sequestration and CO_2 emissions? (3) What are the tillage methods and residue interactions important in carbon cycling for nutrient-use efficiency? Within a given ecosystem, the soils have a finite capacity to store carbon limited by natural soil formation factors. As a result, agriculture's contribution to these larger global climate change issues will likely be for the short term (25–50 years). Nevertheless, agriculture can help society buy time to develop new technologies and cleaner burning fuels.

Summary

Crop residue management through conservation agriculture can improve soil productivity and crop production by maintaining SOM levels. Two significant advantages of surface-residue management are increased OM near the soil surface and enhanced nutrient cycling and retention. Greater microbial biomass and activity near the soil surface acts as a reservoir for nutrients needed in crop production and increases structural stability for increased infiltration. In addition to the altered nutrient distribution within the soil profile, changes also occur in the chemical and physical properties of the soil. Improved soil C sequestration through enhanced CRM is a cost-effective option for minimizing agriculture's impact on the environment.

Ideally, CRM practices should be selected to optimize crop yields with minimal adverse effects on the environment. Results from many experiments have indicated differing effects of CRM practices on harvested yield. Conflicting results occur due to the large number of complex interactions associated with residue quality, soil-related factors, health of the previous crop, potential susceptibility of the next crop and management options such as cultivar selection, crop rotation and planting date. Results suggest that no one CRM system is superior under all conditions. Thus, farmers have a responsibility in making management decisions that will enable them to optimize crop yields and minimize environmental impacts. Multidisciplinary and integrated efforts by a wide variety of scientists are required to design the best site-specific systems for CRM practices to enhance agricultural productivity and sustainability while minimizing environmental impacts.

Crop residues of common agricultural crops are important resources, not only as sources of nutrients for succeeding crops and hence agricultural productivity, but also for improved soil, water and air quality. The development of effective CRM systems depends on a thorough understanding of factors that control residue decomposition and their careful application within a specific crop production system. Maintaining and managing crop residues in agriculture can be economically beneficial to many producers and more importantly to society. Improved residue management and reduced tillage practices should be encouraged because of their beneficial role in reducing soil degradation and increasing soil productivity. Soil C sequestration contributes to these benefits and can play a significant role in mitigating global climate change. Food security and environmental improvement depend on soil C, a valuable resource, that can be sustainable in agroecosystems through improved, cost-effective CRM.

See also: **Carbon Cycle in Soils:** Dynamics and Management; **Carbon Emissions and Sequestration**; **Cover Crops**; **Cultivation and Tillage**; **Mulches**; **Nitrogen in Soils:** Cycle; **Nutrient Availability**; **Organic Matter:** Principles and Processes; Genesis and Formation; **Organic Residues, Decomposition**

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