Implications of crop residue management and conservation tillage on soil organic matter[1]

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Dormaar, J. F. and Carefoot, J. M. 1996. **Implications of crop residue management and conservation tillage on soil organic matter.** Can. J. Plant Sci. **76**: 627–634. Under natural grassland or native prairie, aboveground residue or surface litter modifies the microenvironment. It promotes water infiltration and, by insulating the soil surface, moderates soil temperatures and limits evaporation. Root mass decomposes and transforms within the conditions created by surface litter. Together with root exudates, this below-ground residue or subsurface litter reacts with soil minerals to form aggregates, lower bulk density and increase water-holding capacity. Bringing such soils under cultivation leads to lower soil organic matter content, thereby increasing bulk density. The role of surface litter becomes even more important, as it affects wind and water erosion, reduces the impact of raindrops, prevents crusting, protects the soil from drying by sublimation, and captures snow. Management of crop residues depends on the role of the residue. A distinction must be made between above- and below-ground residues: their roles are distinctly different. Aboveground crop residue protects the soil and creates the conditions for below-ground residue to decompose and transform. These decomposition products, in turn, create favourable soil structure for plant growth. Research is needed on the effect of repeated harvesting of "excess" aboveground residues.

Key words: Labile organic matter, resilience, resistance, surface litter, subsurface litter

Dormaar, J. F. et Carefoot, J. M. 1996. **Conséquence de la gestion des restes de cultures et de la pratique du travail de conservation sur la matière organique du sol.** Can. J. Plant Sci. **76**: 627–634. En prairie naturelle, les restes de cultures laissés à la surface du sol — la litière — modifient le micro-environnement. Ils stimulent l'infiltration de l'eau, modèrent la température du sol et limitent l'évaporation. La décomposition et la transformation de la biomasse racinaire sont intimement reliées aux conditions créées par la litière. De concert avec les exsudats racinaires, cette couche de résidus formée sous la surface du sol réagit avec les minéraux du sol, formant des agrégats, abaissant la densité apparente et accroissant la capacité de rétention de l'eau. La mise en culture de ces sols provoque une baisse de leur teneur en matière organique et, du fait même, un accroissement de leur densité apparente. Le rôle de la litière devient alors encore plus important par son influence sur l'érosion éolienne et hydrique. Elle amortit l'impact des gouttes de pluie, empêche la battance, protège le sol du dessèchement par sublimation et retient la neige. La gestion des restes de cultures doit tenir compte du rôle des résidus particuliers, lequel est nettement différent selon que les résidus se trouvent à la surface du sol ou en dessous. Les restes laissés à la surface protègent le sol et ainsi créent des conditions qui permetent à la couche organique souterraine de se décomposer et de se transformer. A leur tour, ces produits de décomposition améliorent la structure du sol, le rendant plus propice à la croissance des cultures. Il reste à examiner les effets de l'enlèvement répété des résidus superficiels jugés excédentaires.

Mots clés: Matière organique labile, résilience, résistance, litière, couche organique

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Production and decomposition of surface and subsurface litter is an almost continuous process in a grassland. The production/decomposition cycles of native prairie litter serve as a model against which to compare existing and modified litter management systems of cultivated crops. This is not to say that whatever management system is adopted must approach the prairie landscape steady state. The prairie landscape only sets a baseline.

Surface litter can be defined as the uppermost layer of organic debris on the soil surface — essentially the freshly fallen or slightly decomposed vegetal material. The decomposition of the surface litter often begins while the material is still attached to the plant. With time, much of the decomposing litter is mineralized, while the remainder becomes a part of the upper soil horizon. Subsurface litter is the collective organic debris within the soil; this can be root mass, sloughed root cells, and soil-incorporated surface litter. Decomposition products of roots and plant products such as exudates, secretions, plant mucilages, mucigels, lysates, as well as water-soluble organic compounds contributed by surface litter, all have an impact on soil physical properties.

NATURAL GRASSLANDS

Within the natural grasslands, surface litter serves both physical and chemical functions. Dead plant material, whether in the plant canopy (standing litter) or on the soil (fallen litter), has a large influence on the productivity, biomass accumulation and species composition of plants and animals of a region (Knapp and Seastedt 1986). Physically,

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the microenvironment of grassland soil is significantly modified by plant litter (Willms et al. 1986; Willms 1988). It promotes water infiltration, reduces radiation density and insulates the soil surface, cooling the soil in spring and summer while limiting evaporation. It provides a favourable environment for soil microorganisms.

Soils under natural grasslands vary, in part, due to different levels of organic matter associated with moisture levels, texture and carbonation. On Canada's prairies, soils range from Brown Chernozemic (2 to 5% organic matter) under Mixed Prairie with 300 mm precipitation to Black Chernozemic (12 to 17% organic matter) under Fescue Prairie where precipitation is 500 mm. Even though some of the surface litter may eventually become a part of the subsurface organic matter, in grassland ecosystems most of the organic matter input to the soil is through subsurface residue or root litter. Although root litter input is often similar in Mixed and Fescue Prairie ecosystems, abiotic fragmentation of the root litter, caused by repeated freezing and thawing, is significantly greater in the Mixed Prairie, mainly because of overwinter conditions (Dormaar and Willms 1993). As a result, the root litter mineralises faster under the Mixed Prairie soil-forming conditions than under those of the Fescue Prairie. Further, humus is the relatively biodegradation-resistant fraction of soil organic matter. Humification, the biological, microbial or chemical conversion of organic residues to humus, increases from arid to humid soil environments. As a result, there is an increase in humified, more stable, organic matter across the gradient from Brown to Black Chernozemic soils (Dormaar 1992).

Grazing affects the quantity and quality of litter on grasslands. Increased grazing intensity (over the long-term) alters the species composition of a grassland by shifting the competitive advantage to species that are smaller, more shallow rooted, and less productive, but more resistant to grazing and more tolerant of drier soil conditions resulting from surface litter removal. Therefore, while surface litter accumulation is affected by grazing over the short-term, litter production and, presumably, quality are affected over the long-term by new species composition. Litter on rough fescue (*Festuca scabrella* Torr.) grassland was reduced from 12 403 kg ha^{-1} on ungrazed range to 247 kg ha^{-1} by heavy grazing (4.8 Animal Unit Month ha^{-1}) (Peake and Johnston 1965).

Plant canopies and surface litter in the natural environment can alter the chemical composition of precipitation passing through them (Knapp and Seastedt 1986; Gilliam 1987). Hence, the chemical properties of soil under litter are affected both by the quality and quantity of surface litter as well as by the chemical composition of the rainwater falling through the litter. Many hydroxyl- and carboxyl-containing compounds are released during the decomposition of litter by abiotic and biotic agents and may be leached into the soil by precipitation (Dormaar and Willms 1992). In the soil, these compounds have both detrimental and beneficial ecological consequences (Whittaker 1970; Rice 1984). Compounds in extracts from grassland litter can exhibit phytotoxic effects on the germination of various range grasses (Johnston 1961; Bokhari 1978) and affect competition among species (Rice 1984).

Organic matter is high in undisturbed, steady-state soil because little native vegetation is removed, erosion is negligible, wetting and drying are slow, and oxidation is at a minimum due to the absence of artificial soil mixing. Root and crown tissue production is much greater for native grasses than for cultivated crops, and comprises a higher proportion of net primary productivity (Sims and Singh 1978; Sala et al. 1988).

CULTIVATED SOILS

Cultivation not only aerates and mixes the soil, but also causes a physical breakdown of aggregates by intensifying wetting and drying cycles, thereby intensifying abiotic and biotic decomposition processes. Organic matter is lost rapidly. This loss is usually exponential, with rapid declines during the first 10 to 20 yr, followed by smaller annual losses, finally approaching a new equilibrium in 50 to 60 yr (Campbell et al. 1986). The Ah horizons of the prairies have lost 35 to 50%, based on concentration, or 15 to 30%, based on mass, of their organic matter since they were broken 100 yr ago. The initial carbon loss is not only the result of a rapid depletion of the easily mineralizable organic matter fraction but also of dilution with lower carbon containing B horizon material. Removal of the wind-movable fraction contributes considerably to this rapid loss of soil organic matter (Dormaar 1987). In recent years, the effect of farming practices, especially those involving crop residue utilization, crop rotation, and tillage, on equilibrium organic matter levels and on soil quality and productivity has received a lot of attention.

The roles of surface and subsurface litter are distinctly different. Aboveground residues (anchored litter) control wind and water erosion, diminish the impact of raindrops, trap snow, protect the soil from freeze-thaw cycling and drying by sublimation, reduce evaporation thereby increasing water storage, modify soil temperature, regulate infiltration rate of precipitation and generally create a microclimate different from that of bare soil. Surface litter creates the conditions for subsurface residue to decompose and interact with the mineral component of the soil, creating, in turn, favourable chemical and physical conditions for plant growth. These advantages outweigh their disadvantages, such as the potential build-up of rodent and insect populations, overwintering of diseases, and increased potential for the formation of phytotoxic compounds. As surface litter breaks down, water-soluble organic compounds leach into the soil, and potential crop nutrients are deposited on or leached into the soil. Understanding crop residue decomposition is important for assessing the effect on the soil of management practices.

When aboveground residues were repeatedly removed, there was a tendency for soil organic nitrogen to be depleted (Campbell et al. 1991). Conversely, soil organic matter content was not affected (Dormaar 1983; Campbell et al. 1991), supporting the conclusion that, even under cultivation, roots contribute more to maintenance of soil organic matter than do aboveground residues. Conversely, Hooker et al. (1982) established that physical removal of residue of an irrigated cereal crop significantly lowered the organic

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matter content of the soil. Crop rotation, including summerfallow, crop type, including volume and chemical composition, and timing of residue incorporation (e.g., autumn vs. spring) may all contribute to these conflicting results. However, repeated removal of crop residues by burning seems to consistently deplete soil organic matter content (Dormaar et al. 1979; Biederbeck et al. 1980; Hooker et al. 1982; Rasmussen and Parton 1994). It is obvious that information concerning long-term influences of crop residue removal on soil organic matter content, as affected by soil type, time of removal, and amount and method of removal, is still limited.

Surface litter goes through a series of transformations such as physical fragmentation and leaching of water-soluble compounds. However, decomposition of surface litter is much slower than that of subsurface litter (Dormaar and Pittman 1980; Holland and Coleman 1987). Over a 19-mo period, although actual residue loss per se can be 34%, the carbon content of surface straw of unfertilized wheat can decrease by about 14% as cold-water soluble constituents and readily available carbon pools are removed by leaching and microbial assimilation. Although readily available and total carbon in wheat residues decrease progressively, recalcitrant fractions increase (Collins et al. 1990). Subsurface organic residue, on the other hand, may lose 50% of its carbon content under a wheat-fallow regime (Dormaar and Pittman 1980). Litter exposed to air is decomposed mostly by fungi, because fungi resist drying or water stress better than bacteria. Hence, fungal biomass in surface straw was 144% of that on incorporated straw (Holland and Coleman 1987). Even though fungi, with their extensive hyphal networks, are able to utilize both the surface straw carbon and nitrogen in the soil, much straw carbon may subsequently be bound into the relatively undecomposable fungal biomass. Hence, the structure of the aboveground microbial community can affect carbon retention.

Although decomposition and transformation of aboveground residue is generally discussed as a biotic (microorganisms and mesofauna) process, abiotic (physical, chemical and photochemical) routes have also been established. For example, ultraviolet-B radiation (280 to 320 nm) has been implicated as an important agent of plant litter decomposition, since it solubilized straw carbon (H. H. Janzen, unpublished data). Photochemical decomposition processes may well play a significant role in the arid and semiarid wheat growing regions.

CROP RESIDUE MANAGEMENT

Farmers probably applied litter removed from the forest floor to ploughed fields before the Iron Age. Natural mulching remains a common practice in low-technology agriculture and in modern horticulture (Facelli and Pickett 1991). In traditional mixed farming, virtually the whole of the plant was returned to the soil either directly or via animal excreta.

In contemporary agriculture, even though aboveground residues of cultivated crops, such as wheat straw, play a direct soil-protective role and an important indirect role in soil organic matter formation, they are often regarded as waste materials and are removed by baling or burning. Burning straw is now strictly regulated or even banned in many areas, even though it is primarily a response to air quality concerns. However, society has an increasing interest in obtaining energy from biomass (Abelson 1980; Doran et al. 1984). This may be justified in certain instances such as for large quantities of corncobs and stalks. However, biomass removal must be balanced against the cost of non-renewable resources which have to be used eventually as fertilizers are needed to replace plant nutrients in removed residues. Non-renewable resources are also needed as energy needs rise with increased tractor draught requirements, because of organic matter decline and reduction in soil physical conditions.

Part of the rationale of harvesting excess straw for fuel or fibre is the assumption that excess crop residue leads to an increased nitrogen requirement for soil microorganisms to decompose the straw (McGill et al. 1981; Campbell et al. 1986). Carefoot et al. (1994) established that autumn incorporation of straw did not affect plant nitrogen uptake compared with straw removal, while spring incorporation of straw reduced plant nitrogen uptake. Immobilization of nitrogen by incorporation of residues during maximum crop uptake periods increases the requirement for extra nitrogen. The most efficient crop residue tillage system releases nitrogen at the time of maximum crop nitrogen uptake.

Research is needed to determine how much residue can be removed from soils under different tillage and cropping practices, under particular soil, topographic, and climatic conditions, without increasing surface crusting and erosion (Larson et al. 1978) and without jeopardizing the beneficial influence of aboveground residues on below-ground residues. That is, how much residue must be maintained on the soil to control wind and water erosion and balance nutrient loss? Armbrust (1980) attempted to answer this question by measuring residue decomposition, but no threshold values were established.

Although models provide powerful tools to evaluate concepts concerning the mechanisms controlling organic matter turnover in soil (e.g., Jones et al. 1991; Paustian et al. 1992), it may not be possible to establish generalized threshold values. Each soil, together with its superimposed residue management regime, has its own level of resilience and resistance. Resilience is the ability of a system to return to an average state after disturbance, whereas resistance is the persistence of a system and its ability to absorb changes (Holling 1973). Natural semi-arid to sub-humid ecosystems can be characterised as having very little resistance (Kessler 1994), and man-manipulated monocultures in these areas can be expected to have less resistance. This emphasises the need to understand the resilience and resistance of a soil before "excess" aboveground residue is removed. Fertilizers can fulfil the nutrient requirements of the crop, but in order to enhance and maintain ecosystem resilience via an adequate buffering capacity of the soil (Kessler 1994), both surface residue and organic matter in the soil are essential.

The worth of soil protection is related to the value of the soil, which is vital to the long-term maintenance of the grain-growing areas of the prairies. Therefore, ways of

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accelerating the decomposition of excess residues in situ or management techniques to handle high residue levels are needed. The latter need not be explored for the drier areas of the prairies, since high residue levels generally do not arise except in relatively rare wet years.

The interaction between decomposing plant parts and soil that leads to soil structure is complex. Decomposing plant and plant-related materials form a continuum of intermediate forms rather than discrete, well-defined constituents of a single origin. This, in turn, complicates the measurement of organic matter accumulation and changing soil physical properties.

RESIDUE DECOMPOSITION

Annual additions of small amounts of surface residue, as under natural grasslands or continuous wheat production, are more effective in conserving soil quality than periodic additions of large amounts, as under wheat-fallow systems. Organic matter decomposition is enhanced in wheat-fallow compared with continuous wheat systems through soil mixing and higher soil moisture levels, even if the amounts of residue produced are the same over a 2-yr period. Inclusion of alfalfa-grass in a dryland spring wheat rotation did not improve soil organic matter levels above those maintained by continuous wheat production (Janzen 1987). Any factor that increases yield also tends to favour replenishment of soil organic matter through increased root mass.

Surface and subsurface litter production and decomposition in a grassland is an almost continuous process. Conversely, under cultivation, surface litter is produced in surges. Following the grain harvest, there are three major steps within the life cycle of the crop residue: decomposition and mineralization of the surface litter in situ; incorporation of part of this surface residue into the soil by human and/or animal activity and via leaching of water-soluble compounds; and decomposition of the subsurface residue (litter + water-soluble organic compounds + root mass). It is this third step that has the greatest effect on the soil biological, chemical and physical properties. Within this cycle minerals are released from crop residues and reabsorbed by new plant growth. Factors such as soil moisture, temperature and texture affect the below-ground decomposition.

Decomposition pathways are assumed to be similar under native prairie, irrigated pasture, and wheat monoculture. Residues generally contain lignins, carbohydrates, fats, proteins and minerals. Differences in decomposition are mainly a matter of rate controlled by levels of inputs and losses under management practices such as tillage, irrigation and fertilizer application. Since these controls change with time, e.g., from day to night and season to season, decomposition is never in equilibrium but rather is an ongoing process (Dormaar 1992).

The effect of the chemical composition of residues on decomposition has been studied from a variety of aspects. Spaulding and Eisenmenger (1938) found that the rate of decomposition of different types of plants, when incorporated into soil, varied according to the anatomical structure and the chemical composition of the plant. Janzen and Kucey (1988) demonstrated a dominant influence of nutrient concentration on residue composition. Douglas and Rickman (1992) estimated crop residue composition from air temperature, initial nitrogen content and residue placement. Thus, under certain conditions, C/N ratios are likely important indicators of decomposition.

Herman et al. (1977) took more plant characteristics into account. They incubated roots of rough fescue, porcupine grass (*Stipa spartea* Trin. var. *curtiseta* Hitchc.), and spear grass (*Stipa comata* Trin. and Rupr.) at 28°C for 47 wk and found no single property of the original material, such as C/N ratio, lignin content, or carbohydrate content was a good predictor of rates or changes during decomposition. However, when these characteristics were combined into a Decomposition Index, i.e., (C:N) (% lignin)/(carbohydrate$^{-0.5}$), relative rates of decomposition and changes during decomposition were accurately predicted.

The Decomposition Index (Herman et al. 1977) not only explains the differences in the level of organic matter in soils under different plant communities, but also differences with time in the same plant community. Seasonal fluctuations in chemical characteristics of roots of blue grama [*Bouteloua gracilis* (H.B.K.) Lag.] in situ can be related to their chemical characteristics. The root mass decreases from autumn to spring, a period when chemical and biological activities are low and biological decomposition is almost at a standstill (Dormaar et al. 1981). The chemistry of the root mass may influence this decrease. The decomposability expression indicated that roots collected in the autumn were potentially the least resistant and roots collected in the early summer were potentially the most resistant to decomposition. This may explain the differences in nitrogen uptake observed by Carefoot et al. (1994) after autumn and spring incorporation of straw.

CONSERVATION TILLAGE

Conversation tillage refers to soil management practices which maintain crop residues on the soil surface, generally by reducing tillage. A number of excellent reviews (Unger and McCalla 1980; Blevins and Frye 1993) list three goals: to leave enough plant residue on the soil surface at all times for water and wind erosion control, to reduce energy use, and to conserve soil and water. The optimal soil protection and soil organic matter levels depend on the constraints of the steady state of the particular management system.

The Conservation Technology Information Centre, Lafayette, IN, defines conservation tillages "any tillage and planting system that maintains at least 30% of the soil surface covered by residue after planting to reduce water erosion, or, where soil erosion by wind is a primary concern, maintains at least 1135 kg·ha^{-1} of flat, small grain residue equivalent on the surface during the critical wind erosion period" (Blevins and Frye 1993). According to this definition, reduced and minimum tillage may or may not qualify as conservation tillage depending on the level of residue remaining at the soil surface after planting. However, none of these or similar definitions really says anything about the potential of increased surface residue to influence soil properties.

As with grassland surface litter, the role of surface litter from cultivated crops differs from that of root litter. Besides

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preventing erosion, surface residues affect the soil physical environment (Van Doren and Allmaras 1978; Unger and McCalla 1980). Since surface litter prevents surface sealing and crusting, it improves soil aeration and pore size distribution. Surface plant residues can reduce soil temperature by changing the radiant energy balance and insulating the soil. This may slow germination and seedling emergence. The effect of lower soil temperature on germination may be partly compensated for by shallower seeding depths allowed by higher soil moisture. Relative advantages and disadvantages are influenced by factors such as weather, tillage system, cropping rotation, and the unique properties of individual soils.

SOIL CHEMICAL PROPERTIES

Soil physical properties are influenced by the amount and quality of soil organic matter. Soil organic matter depends not only on some above- and all below-ground residue, but also on the quality and management of this residue. Since, with conservation tillage, little mixing occurs in the upper part of the soil, a profile is formed in the original Ap horizon. Rasmussen and Collins (1991), summarizing a variety of studies, concluded that although, compared with conventional methods of tillage, conservation tillage increased organic carbon and nitrogen in the top 5 to 15 cm of soil, the net change in the soil profile was not as great as might be expected, because organic matter was concentrated near the soil surface.

Plant roots tend to proliferate in the upper Ap horizon, thereby increasing soil aeration. However, plant roots exude a variety of organic compounds that affect the mineral component of the soil directly or indirectly via the microbial population in the rhizosphere. Due to increased root mass, monosaccharide levels increase as do dehydrogenase and phosphatase activities (Dormaar and Lindwall 1989). Doran (1980) established that the no-till ecosystem resembles other undisturbed soil ecosystems such as native grassland. That is, Ap horizon levels of carbon, nitrogen and water are higher than those of tilled land, while the average metabolic status of higher microbial populations is less oxidative. Soil organic matter qualities therefore differ in conservation and conventional tillage.

SOIL PHYSICAL PROPERTIES

Crop residues play an important role in maintaining good soil physical conditions. In most climates, the removal of all residues from the field, e.g., for use as fuel or by heavy field grazing, leads to deterioration of soil physical properties (Kladivko 1994).

Soil structure has been defined as "the spatial heterogeneity of the different components or properties of soil" (Dexter 1988). A successful crop production system must maintain the soil's physical quality. Soil structure can determine both the effectiveness and the impact of farming practices on water infiltration and soil erodibility, which, in turn, depend on such soil physical properties as aggregation, bulk density, hydraulic conductivity, water-holding capacity, and porosity (Kay 1990). All these properties depend on the amount and quality of organic matter in the soil.

Chang and Lindwall (1990) examined the long-term effects of summerfallow–wheat rotations and continuous wheat under conventional and conservation tillage on soil erosion and soil and water conservation by measuring such soil physical properties as bulk density, saturated hydraulic conductivity, plant-available water-holding capacity, aggregation of soil particles and air-filled porosity. The most significant effects of long-term tillage or crop rotation treatments in soil properties were observed in the 30- to 60-mm depth. After 10 yr of continuous no-till cropping, this layer tended to have a lower saturated hydraulic conductivity and higher bulk density than soil from the conventionally tilled treatments. Loss of organic matter and of organic carbon-rich Ap horizon soil under conventional tillage increased bulk density. Seventy years of cultivation in the Canadian prairies has increased the bulk density of surface soil by 16% (Voroney et al. 1981).

Water-stable aggregates encourage water infiltration, thereby influencing soil and water conservation, maintain soil quality (tilth) and improving plant emergence, enhance the activity of biota, and prevent water and wind erosion. Soil aggregation refers to the cementing or binding together of several soil particles into secondary units in such a way that they behave mechanically as a unit. Soil aggregates can be divided into two classes: macroaggregates >250 μm in diameter and microaggregates <250 μm in diameter. Dexter (1988) subdivided the microaggregate fraction into three subclasses: quasi-crystals or domains (1 to 2 μm diameter) composed of combined primary (clay) particles, clusters (2 to 20 μm diameter) composed of quasi-crystals, and microaggregates (2 to 250 μm diameter) composed of clusters. Different physical, chemical and biological mechanisms are involved in the formation of each subclass (Dormaar and Foster 1991). The terms "soil structure" and "soil aggregation" are often used synonymously, but soil aggregates are the basic units of soil structure, rather than of the whole soil.

A stable macroaggregate may be a collection of microaggregates, stabilized by a network of roots and fungal hyphae, or one large aggregate, stabilized by polysaccharides (Tisdall and Oades 1982). In fact, macroaggregates are generally a mixture of the two possibilities. The more root mass and vesicular-arbuscular mycorrhizae are maintained in the soil, whether by pasture or annual cropping, the greater the stability of the soil, through physical and chemical stabilization of macroaggregates. Organic residues, bacteria, polysaccharides and inorganic materials are particularly involved with stabilizing microaggregates.

The organic matter content of soils, and especially the carbohydrate fraction, is one of the few factors highly correlated with aggregate stability. Its presence increases microbial biomass around roots, thereby increasing metabolic secretions, which enhance aggregate stability. Up to 56% of a cultivated soil can be in the <100-μm aggregate fraction (Dormaar 1983, 1987). This fraction can have up to twice the organic matter of the remainder of the soil and up to four times the organic matter of the same fraction in the uncultivated soil of nearby native prairie. If this fraction, with its higher organic matter content, is removed by ero-

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sion, the water-holding capacity of the soil can be seriously reduced (Dormaar 1987).

In terms of chemical constituents, there appear to be two stages to the formation of stable aggregates (Haynes and Swift 1990): an aggregation phase involving exocellular microbial polysaccharide mucigels (Dormaar and Foster 1991) and a stabilizing phase which involves humic materials (Dormaar 1983). Polysaccharides are an excellent energy source for the soil microbial population and, hence, transitory binding agents. They must be continually replenished via root exudates and products from bacteria, if they are to contribute to long-term aggregate stabilization. The greater the root mass (annual cropping) and the more often it is replenished, the more regular the supply of polysaccharides. Hence, the supply of organic matter by roots and microorganisms must be maintained and protected from further microbial attack.

Dehydrogenase activity has been found to be higher under a no-till treatment than under a blade-cultivated treatment (Dormaar and Lindwall 1989). Soil moisture increases with the increase in water-holding capacity of the soil as a result of increased organic matter levels of the soil and with the decrease in soil temperature associated with increased levels of aboveground residue of the no-till regime. Doran (1980) concluded, on the basis of ratios of microbial populations in no-till and cultivated soil, that the environment under no-till was "less oxidative", implying more anaerobic microbial processes, such as denitrification and fermentation. Chendrayan et al. (1980) ascribed the marked increase in the dehydrogenase activity of soils, observed under the anaerobic conditions following flooding, to an increase in the population of anaerobic microorganisms. Hence, increased dehydrogenase activity may be expected under no-till management systems due to increased anaerobic microbial processes.

The determination of dry-soil aggregate size distribution attempts to quantify the potential disintegrating forces of wind erosion. The potential for movement by wind is, to a large extent, a function of aggregate size distribution (% <840 μm) and, to some extent, of density. Size can be reduced and erodibility increased by, among other factors, freezing, thawing, wetting and drying.

In the absence of adequate surface roughness and moisture, wind erosion may occur when large highly erodible fractions combine with low levels of residue cover. Larney et al. (1994) warned that these two conditions can counteract each other as the treatment with the highest surface residue cover (zero tillage) also has the highest erodible fraction (>60%). Loss of surface residue cover, e.g., by fire, can lead to the loss of an Ap horizon with good tilth, established under zero tillage (I. Lanier, personal communication).

FUTURE RESEARCH

Management of residue depends on the role of the residue. Aboveground crop residues protect the soil surface against winter-associated decay of soil structure, wind and water erosion, improve soil moisture budgets, and create suitable conditions for below-ground residue to decompose and transform. Conversely, below-ground residue contributes to soil organic and physical properties or soil quality. There is the physical and chemical contribution of root mass per se to the soil and the transformation of residue to a wide array of soil organic matter products affecting soil physical and nutrient properties. Aboveground residue's role is mainly acted out in an unchanged physical form, while below-ground residue's role is mainly acted out in a transformed chemical form.

A balance must be struck between maintaining the below-ground organic matter supply for optimal physical conditions, such as water-stable aggregates, bulk density and water-holding capacity, via maintenance and increase of root mass, and the aboveground organic matter supply for optimal erosion protection and soil physical conditions, such as lower soil temperature and decreased evaporation, via maintenance and increase of surface litter. This balance between aboveground and below-ground organic matter under grassland was a dynamic equilibrium. Management and tillage strategy can affect this equilibrium.

The contribution of aboveground residue to soil organic matter is secondary to its role in creating the proper hydrothermal conditions for below-ground residue to transform to soil organic matter. How many years of removing aboveground litter does it take to start decreasing soil organic matter levels? In less than 20 yr of eliminating aboveground litter by overgrazing, a Black Chernozemic soil was changed to a droughtier Dark Brown one with a vegetation association with a root mass dependent on more frequent rain events (Johnston et al. 1971).

Soil organic matter is of great concern in semiarid climatic regions. However, land managers have many soil protecting options. Although Klemmedson (1989) ruefully observes that land managers have been hesitant to select these options because of economic considerations, much has been accomplished in regard to the use of crop residue on the surface in conservation tillage systems. To further understand the role of crop residues, research is needed to evaluate effects of management on soil organic matter fractions resulting in differences in stability and effects of biological significance. For example, Janzen (1987) found that levels of mineralised organic matter were closely related to levels of "light fraction" material (specific gravity <1.59 cm^{-3}), which is believed to consist primarily of incompletely decomposed organic matter of plant origin. One management tool, crop rotation, has a pronounced effect on the distribution of organic matter among labile and recalcitrant organic matter. Once the separate physical, chemical, and biological components of the plant-soil environment, both above- and below-ground, are understood via reductionist research in terms of the use of crop residue on the surface in conservation tillage systems, an integrative synthesis to describe the changed soil environment will be needed.

Recent research (Beare et al. 1994) suggests that saprophytic fungi have a major influence on the decomposition of surface-applied crop residues in conservation tillage, while bacteria are the main agents for the decomposition of incorporated residues in conventional tillage. Fungal-mediated binding of soil macroaggregates is considerably greater under conservation tillage than in conventionally tilled soils. This suggests that a fungal-dominated microflora likely produces binding agents that differ chemically from those of other microbial communities. Since such differences would influence the biodegradability of these binding agents, further research is required to understand the chemistry behind the processes. This may then allow the development of optimal residue management systems to protect the surface of the soil and to improve the soil physical properties.

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