MANAGING AGRICULTURAL RESIDUES

Edited by

Paul W. Unger, Ph.D.

Soil Scientist
Conservation and Production Research Laboratory
U.S. Department of Agriculture
Agricultural Research Service
Bushland, Texas

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CHAPTER 6

Influence of Crop Residues on Nutrient Cycling and Soil Chemical Properties

Harry H. Schomberg, Paula B. Ford, and William L. Hargrove

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I. INTRODUCTION

Historically, crop residues have played an important role as a mulch for soil and water conservation and as an input for maintaining soil organic matter and returning nutrients to soil. After World War II and the advent of commercial fertilizers, utilization of crop residues as a source of nutrients diminished in many developed countries. In the U.S., the role of crop residues is being reexamined as emphasis on reduced tillage, reduced purchased inputs, and environmentally sound agriculture increases. With greater emphasis on agricultural sustainability, crop residues are becoming an integral component of many cropping systems. Successful integration of residue management strategies into these cropping systems requires an understanding of how crop residues influence nutrient cycling and soil chemical properties.

II. CROP RESIDUES AND SOIL PRODUCTIVITY

Crop residues play an important role in maintaining soil productivity by providing a source of nutrients and inputs to organic matter.[1] The contribution of crop residues to soil productivity is frequently cited as a primary benefit associated with conservation tillage cropping systems. While a significant amount of research has focused on reducing soil erosion with crop residues, the role of crop residues in maintaining (or increasing) organic matter content is also of primary importance to soil productivity.

A. Role of Soil Organic Matter in Maintaining Soil Fertility

Soil organic matter is the major source of nitrogen (N), sulfur (S), phosphorus (P), and many minor nutrients in soils[1,2] and is critical to efficient crop production because of its cation exchange and water holding capacities. Studies in the Great Plains and other areas have shown that soil organic matter decreases when virgin land is converted to cropped land (Figure 1).[3,4] Generally, rapid reductions in organic matter occur during the first 10 to 20 years, with more gradual declines over subsequent years.[5] Microbial degradation of organic matter increases following cultivation due to increased substrate and O_2 availability. Additionally, removal of harvested biomass plus reduced organic matter inputs from crop root systems, as compared to native sod or grass root systems, increases organic matter depletion rates.[6]

B. Contribution of Residues to Soil Organic Matter Maintenance

Crop residues, including roots, are the primary source of organic material added to soil in many cropping systems. Soil organisms use residues as a source of energy and nutrients, thereby releasing CO_2, inorganic compounds, and recalcitrant molecules, which contribute to the formation of soil humus. Crop residues represent a major contribution to nutrient cycling, as indicated by average N, P, S, and potassium (K) concentrations of some crop residues presented in Table 1.[7] The data from Table 1 and annual yield data from the U.S. Department of Agriculture (USDA)[8] were used to estimate the quantity of N, P, and K returned to soil through residues in the U.S. (Table 2). The value of nutrients in crop residues is considerable, especially for the major crops.

Crop residue chemical composition plays an important role in determining decomposition rates. Degradation of crop residues releases about 55 to 70% of the carbon to the atmosphere as CO_2, 5 to 15% is incorporated into microbial biomass, and the remaining C (15 to 40%) is partially stabilized in soil as new humus.[9,10] Early in the decomposition process, rapid loss of simple sugars and amino acids may occur within a few hours to a few days, while polysaccharides, proteins, and lipids decompose at much slower rates.[10] Lignin makes up 5 to 30%

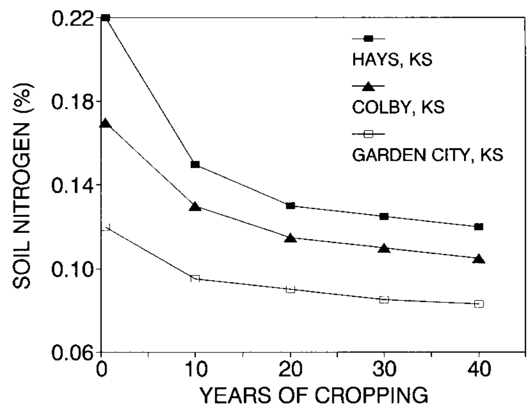

FIGURE 1. Change in total N, which can be equated with changes in soil organic matter, for three soils in western Kansas. (From Haas, H. J., Evans, C. E., and Miles, E. F., Nitrogen and Carbon Changes in Great Plains Soils as Influenced by Cropping and Soil Treatments, Tech. Bull. No. 1164, U.S. Department of Agriculture, U.S. Government Printing Office, Washington, D.C., 1957.)

Table 1. Nutrient Concentration of Unharvested Above-Ground Portion of Plant

Crop	Botanical name	Nitrogen	Phosphorus	Potash	Sulfur
Alfalfa	*Medicago sativa*	2.09	0.18	1.78	0.25
Barley	*Hordeum vulgare*	0.69	0.07	2.37	0.17
Clover, crimson	*Trifolium incarnatum*	2.91	0.22	2.40	0.28
Clover, red	*Trifolium pratense*	2.72	0.25	1.62	0.17
Corn	*Zea mays*	0.95	0.10	1.45	0.17
Cotton	*Gossypium* spp.	0.90	0.15	1.45	—
Cowpea, common	*Vigna sinensis*	0.49	0.35	2.26	0.35
Oats	*Avena sativa*	0.70	0.06	2.57	0.23
Peanut	*Arachis hypogaea*	1.71	0.15	1.38	0.23
Rice	*Oryza sativa*	0.69	0.08	0.57	0.09
Rye	*Secale cereale*	0.48	0.09	0.97	0.11
Sorghum	*Sorghum bicolor*	0.83	0.13	1.20	—
Soybean	*Glycine max*	0.83	0.47	0.93	0.30
Sunflower	*Helianthus annuus*	0.80	0.15	0.92	—
Wheat	*Triticum aestivum*	0.58	0.05	1.42	0.19

Note: Values are %.

From National Research Council (U.S.) Subcommittee on Beef Cattle, *Nutrient Requirements of Beef* Cattle, 6th ed., National Academy of Sciences, Washington, D.C., 1984, chap. 7.

of crop residue material and is more resistant to decomposition than other plant constituents. Lignin is an important substrate for soil humus formation due to its resistance to decomposition.[1,2]

C and N availability within crop residues along with lignin content greatly influence decomposition rates and N availability to plants.[11-13] Decomposition of residues with low N contents such as wheat (*Triticum aestivum* L.) and grain sorghum (*Sorghum bicolor* [L.] Moench) may result in microbial immobilization of soil and fertilizer N, effectively reducing N availability to plants. In general, residues with N concentrations below 1.5% or C:N ratios greater than 30 are considered to immobilize inorganic N. However, use of critical C:N ratios and initial N contents to determine N immobilization and mineralization patterns has been criticized because they are site (soil N content) and species specific. Additionally, residues with very similar C:N ratios can have different decomposition rates because of variations in

Table 2. Estimated N, P, and K Content in Residues Returned to Cropland Annually in the U.S.

Crop	Area harvested (1000 ha)	Harvested yield[a] (1000 Mg)	Harvested portion	Crop residue (1000 Mg)	Nutrients in Residue (Mg)		
					N	P	K
Barley	3,090	6,314	0.4	9,471	65,350	6,630	224,463
Beets	526	25,466	0.9	2,830	76,398	6,225	164,114
Corn	23,571	125,194	0.4	187,791	1,784,015	187,791	2,722,970
Cotton	4,837	3,356	0.4	5,034	45,306	7,551	69,469
Oats	2,239	3,158	0.4	4,737	33,159	2,842	121,741
Peanuts	659	1,640	0.4	2,460	41,820	3,690	33,948
Rice	1,174	7,253	0.4	10,880	75,069	8,704	62,013
Rye	241	373	0.4	560	2,686	504	5,427
Sorghum	4,066	15,694	0.4	23,541	195,390	30,603	282,492
Soybeans	23,218	42,152	0.3	98,355	816,344	462,267	914,698
Sunflower	777	813	0.3	1,897	15,745	2,846	17,642
Wheat	21,525	49,320	0.4	73,980	429,084	36,990	1,050,516

[a] Harvested yield is the portion of crop removed at harvest. Harvested yield + residue = total plant biomass at harvest.

From U.S. Department of Agriculture, Agricultural Statistics 1990, U.S. Government Printing Office, Washington, D.C., 1990, 372, and from Table 1.

chemical constituents.[10,14] Availability of residue N to microorganisms may vary because of its presence in highly resistant compounds or due to physical protection by lignin within residues.[10]

Environmental conditions, initial soil N content, and soil microbial populations also affect residue decomposition rates.[15,16] Water and temperature are primary climatic factors influencing organic matter decomposition. Generally, decomposition rates are faster in warm, humid areas and decrease as water availability and temperatures decrease. The interactions between water availability and temperature that control decomposition rates are complex.[17-19] Soil microorganisms function at temperatures from 0 to 60°C, with maximum growth and activity occurring between 25 and 35°C.[20] Significant microbial decomposition of wheat straw can occur at temperatures as low as 0°C, but maximum activity is near 30 to 35°C.[21,22] Optimum water potential for residue decomposition occurs between soil water potentials of -0.03 and -0.1 MPa. Bacterial respiration declines rapidly as potentials decline below -0.3 MPa, while fungal activity may continue down to potentials of -4 to -5 MPa.[20,23]

Crop residue placement influences on soil temperature and water regimes (see Chapters 4 and 8) indirectly influence microbial activity and residue decomposition. Holland and Coleman[24] characterized field data on the microclimate of surface residues as having drier soils, highly fluctuating soil temperatures, and drier straw, while the microclimate of incorporated residues had moister soils, less fluctuation of soil temperatures, and moister straw. Faster decomposition rates of buried residues than of surface residues result from greater soil-residue contact, a more favorable and stable microenvironment for decomposition, and increased availability of exogenous N for decomposition by microorganisms.[14,25-28] Hargrove et al.[12] reported that decomposition rates of four different crop residues were significantly greater when residues were incorporated into soil than when they were maintained on the soil surface. Decomposition rates for both surface and buried residues were significantly influenced by initial C:N ratio, lignin content, and lignin:N ratio of the species.

The role of soil organisms as primary agents of decomposition, energy flow, and nutrient cycling has become the subject of increased research since the mid-1970s.[29] Rapid methods of microbial biomass estimation[30-32] together with nutrient flux measurements provide detailed information for more mechanistic analyses of nutrient cycling. Use of ^{14}C- and ^{15}N-labeled substrates and plant material in decomposition studies indicates that C and N in plant litter and plant-derived compounds are readily incorporated into microbial biomass.[33-36] Microbial biomass is, therefore, both a source and sink for nutrients needed for crop production.

Microbial biomass C accounts for 2 to 5% of total soil C, while microbial biomass N represents 1 to 5% of total soil N across different ecosystems.[29] Although these values are only a small portion of total C and N in soils, this living portion of soil contains a substantial amount of nutrients needed for crop growth. Doran[37] showed that the distributions of soil microbial biomass and potentially mineralizable N in long-term tillage comparisons at seven sites in the U.S. were influenced by residue management. Microbial biomass and potentially mineralizable N averaged 54 and 37% higher, respectively, in no-tillage compared to plowed soils. There was a high correlation between microbial biomass and potentially mineralizable N at 0 to 7 cm and 15 to 30 cm, and both measurements were positively related to total soil N. Levels of microbial biomass and potentially mineralizable N were also positively associated with soil organic matter and soil water content with depth.

Estimates of turnover rates for soil microbial biomass range from months to years, with many studies indicating turnover times of less than 1 year.[36] Smith and Paul[29] estimated that microbial biomass contained 60, 47, and 28% of the N, P, and S, respectively, required in above-ground plant biomass for a winter wheat crop grown in the U.S. Pacific Northwest producing 16 Mg/ha dry matter and a 6.7 Mg/ha grain yield. The importance of microbial biomass as a potential source of plant nutrients illustrates the need for understanding how

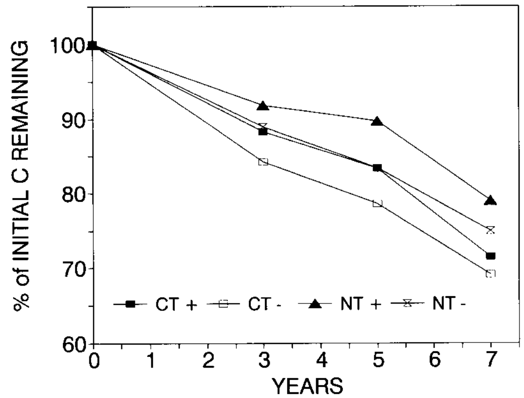

FIGURE 2. Relative change in soil organic C at 0- to 0.1-m depth in a Vertisol during 7 years of conventional tillage (CT) and no-tillage (NT) with (+) and without (−) above-ground sorghum residues. (From Standley, J., Hunter, H. M., Thomas, G. A., Blight, G. W., and Webb, A. A., *Soil Tillage Res.*, 18, 367, 1990. With permission.)

residue management influences movement of nutrients through microbial biomass. Greater knowledge in this area should improve our ability to manage soil nutrient resources efficiently.

III. CROPPING SYSTEM AND TILLAGE INFLUENCES ON RESIDUES

The fate of crop residues following harvest has a tremendous influence on soil productivity. Residues may be managed by removal, feeding to animals, burning, or incorporation or may be left on the soil surface. Where residues are not removed from the field for other uses, burning and tillage significantly alter crop residue impacts on soil productivity. Decomposition of crop residue and organic matter increases following tillage due to increased soil-residue contact and exposure of occluded organic material to decomposing organisms. Residue incorporation effects on soil productivity are difficult to separate from tillage effects because incorporation is accomplished through some type of tillage operation. Removal of surface residues through tillage, burning, or other means indirectly influences soil water content, soil temperature, and porosity. Subsequent changes in the microbial community can affect N availability through reduced mineralization and nitrification and via increased denitrification.[38] Observed increases in organic matter with reduced-tillage systems are largely attributed to reduced decomposition rates of surface residues, as contrasted to rapid decomposition of incorporated residues.[27,39] However, the rate and degree of organic matter accumulation associated with surface residues vary widely due to differences in climate, soil type, and residue quality.[40]

A. Organic Matter Changes Associated with Tillage and Residue Management

Residue management practices that involve frequent and/or intensive tillage and incorporation of residues increase residue decomposition rates and loss of soil organic matter. Standley et al.[41] evaluated the effects of conventional tillage and no-tillage management, with and without residue removal, on organic C in a Vertisol in Queensland, Australia (Figure 2). Annual inputs of grain sorghum stubble (2.0 to 4.3 Mg/ha) were insufficient to prevent a decrease in organic C during the 7-year study. Although not significantly different, trends for organic C loss were greater where sorghum residues were removed and where disk tillage was used during fallow periods.

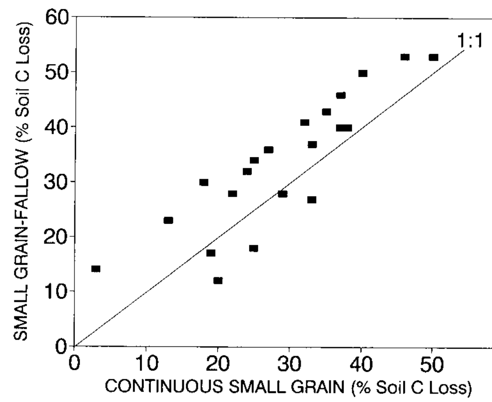

FIGURE 3. Comparison of soil C loss under continuous cropping vs. alternate cropping to small grains for soils in the Great Plains. (From Haas, H. J., Evans, C. E., and Miles, E. F., Nitrogen and Carbon Changes in Great Plains Soils as Influenced by Cropping and Soil Treatments, Tech. Bull. No. 1164, U.S. Department of Agriculture, U.S. Government Printing Office, Washington, D.C., 1957.)

Alternate fallow-crop systems designed to conserve soil water often result in less biomass production and a greater decrease in organic matter than continuous cropping systems. However, this effect depends on the soil and climatic conditions. Haas et al.[3] evaluated soil C and N data for paired continuous and alternate crop-fallow studies from several locations in the Great Plains. They found that alternate crop-fallow systems had greater losses of soil organic matter and N when compared to continuous cropping systems (Figure 3). Decreases in soil C averaged 5% greater for alternate cropping systems compared to continuous cropping over the 30-year cropping period. Overall loss of N averaged 24% for continuous small grain and 29% for small grain-fallow cropping systems. Productivity of these soils decreased due to reduced annual inputs of new organic material. In Texas, Unger[42] showed that, after 24 years of wheat-fallow, soil organic matter declined 35% under one-way disk tillage, but only 17% under a delayed stubble mulch system that allowed residues to remain on the soil surface. Weed growth in the latter treatment may have contributed to maintenance of soil organic matter levels. When soil was continuously cropped to wheat, organic matter declined 14% with one-way disk tillage and 12% with stubble mulch tillage, but the difference was not significant. Bauer and Black[4] compared C and N contents of soils from 12 sites in North Dakota. After 25 years, organic C in moderately coarse- and fine-textured soils averaged 44 and 13% higher, respectively, for stubble mulch tillage than for conventional tillage. Organic C for medium-textured soil was not different due to tillage practice. When averaged across soil textures and compared to virgin sod, soil organic C declined 27% under mulch tillage and 38% under conventional tillage.

In Ohio, Dick[43] found in three crop-rotation systems that organic matter in a silty clay loam declined 0% for no-tillage, 12% for minimum tillage, and 14% under conventional tillage after 18 years. At a second site, organic C declined 11, 23, and 25%, respectively, for the three tillage practices for a silt loam after 19 years. The relative effect of tillage was greater in the silt loam than in the silty clay loam and may have been related to better internal drainage of the silt loam. Also, no-tillage corn grown in the silty clay loam was subject to root damage from *Pythium*. Even so, organic C was 49% greater in the silty clay loam and 58% greater in the silt loam with no-tillage than with conventional tillage at the 0- to 7.5-cm soil depth.

Results from Kansas indicate that tillage effects on organic C and N are influenced by crop rotation.[44] Inclusion of sorghum in rotation with soybean (*Glycine max* [L.] Merr.) resulted in greater soil organic C and N contents for a silty clay loam and a silt loam at 0 to 2.5 cm, but not at greater depths. In the silty clay loam, organic C with no-tillage was 0, 5, and 14%

greater than with conventional tillage for rotations of soybean-soybean, sorghum-soybean, and sorghum-sorghum, respectively. In the silt loam, organic C for no-tillage was greater than conventional tillage by 25, 49, and 40% for the three rotations. The rate of organic C accumulation with increasing residue was about 2.5 times greater with no-tillage than with conventional tillage. In a long-term study of tillage effects on soil properties in Kentucky, organic matter content in the upper 5 cm of soil was approximately two times greater for surface residues compared to residue incorporation.[45] Similar increases in surface organic matter content associated with surface residues have been reported elsewhere.[46,47]

Under conditions of warm temperatures and increased water availability, organic matter accumulation from surface residues is reduced. Even so, the added organic matter can have profound effects on soil productivity in highly weathered, low base status soils.[48,49] For instance, Salau et al.[50] found that mulching plantain (*Musa paradisiaca* L.) with elephant grass (*Pennisetum purpureum* [L.] Schumacher) significantly improved both soil productivity, as reflected in improved soil chemical and physical properties, and total yield compared to a nonmulched system in southeastern Nigeria. Similar results have been obtained on other highly weathered and acid soils in the southeastern U.S.,[51,52] Brazil,[53] and India.[54]

Burning of residues results in loss of organic C, but the magnitude is influenced by the quantity of residue burned and the intensity of the fire. Burning volatilizes a portion of the N contained in residues, but other nutrients are made more immediately available. In Canadian prairie soils, 20 years of wheat-residue burning reduced soil organic C 15 to 20% and total N 4 to 10% compared to a chopped-straw treatment where residues remained on the surface.[55] In Oregon, burning of wheat residues in the fall increased organic C loss compared to spring-burned or no-burn plots.[56] Additionally, soil N losses were 25% greater where residues were fall-burned compared to control plots or to spring-burned residues. Volatilization of N from burned residues was implicated as accounting for most of the difference in soil N. Delayed burning of residues until spring was beneficial in that soil degradation was reduced to a level similar to no-burn plots. Lower soil C and N losses for spring-burned than for fall-burned plots are probably due to partial decomposition and/or leaching of N during winter for spring-burned wheat.

B. Residue Management and Nutrient Distribution

Reduced-tillage practices that leave a larger portion of crop residues on the soil surface greatly reduce decomposition and result in stratification of nutrients and organic matter near the soil surface. Langdale et al.[57] showed that organic C levels in the 0- to 1-cm layer of a soil double-cropped to sorghum and wheat for 4 years were 19% in no-tillage, 14% in mulch tillage, and 12% in conventional tillage. When measurements were based on the 0- to 7.5-cm soil layer, organic C averaged 11% for all three tillage methods. Similar trends for stratification of P and calcium (Ca) were observed, with P and Ca contents of the 0- to 1-cm layer of no-tillage being three times greater than those for mulch tillage and conventional tillage, while no differences due to tillage were apparent when based on the 0- to 7.5-cm soil depth.

After 5 years of double-cropping wheat and soybean on a sandy loam soil in Georgia, nutrient concentration in the soil surface (0 to 7.5 cm) was greater with no-tillage than with conventional tillage.[51] Nutrient content was greatest near the surface and decreased with depth in no-tillage soil, while there was a more homogeneous distribution of nutrients with soil depth in conventionally tilled soil. Ca, P, magnesium (Mg), manganese (Mn), and zinc (Zn) accumulated near the soil surface with no-tillage, but K was lower compared to conventional tillage. Although not significant, organic C and organic N tended to be greater near the surface with no-tillage than with conventional tillage. Greater nutrient (P, K, Ca, Mg, and Zn) accumulation was also observed in a sandy loam soil at 0- to 7.5-cm and 7.5- to 15-cm depths with no-tillage compared to conventional tillage for a double-cropped corn (*Zea mays* L.) and rye (*Secale* *cereale* L.) cover crop system after 3 years.[58] Nutrient accumulation at the surface of no-tillage soil was associated with surface application of fertilizer and crop residues and absence of incorporation. Stratification of nutrients in no-tillage plots was not detrimental to crop growth, since root activity and nutrient extraction were greater in the no-tillage system and average corn yields for the 3-year study were greater with no-tillage than with conventional tillage. However, response of soil pH to lime application was greater for the conventional tillage system due to lime incorporation.

IV. EFFECT OF RESIDUES ON NITROGEN AVAILABILITY

Microbes responsible for N transformations in soil are influenced by soil physical and chemical property changes created by soil management practices, including crop residue management.[38,59] The residue N content and availability of soil N are important determinants of N mineralization-immobilization occurring during residue decomposition.[60] Availability of N from crop residues to subsequent crops is highly dependent on decomposition rate, residue quality, and environmental conditions.[61-63]

A. Benefit of Legume Residues to Nitrogen Fertility

The contribution of crop residues to overall soil productivity is of particular importance with leguminous crop residues. Hargrove[64] found that legume cover crop effects on soil fertility status included lower pH, redistribution of K, and lower C:N ratio of organic matter. Perhaps more important for sustained crop production, leguminous cover crops replaced an estimated 60 to 70 kg N/ha, depending on species grown. The contribution of fixed N from legume residues to cropping systems depends on the symbiotic activity, N removed in the harvested portion of the legume, and availability of soil N to the legume.[60]

Studies with ^{15}N-labeled legume residues indicate that N recovery by subsequent crops ranges from 10 to 35% of the N originally contained within legume residues.[34,65-67] In Minnesota, recovery of ^{15}N-labeled legume N by corn was greater from alfalfa (*Medicago sativa* L.) residues than from soybean residues.[66] Based on whole-plant N content, use efficiency of N from alfalfa varied from 27 to 70% depending on cultivar, location, and cutting treatment. For the two locations (Becker and Rosemont, MN), respective use efficiency of N from nodulated soybean was 18 and 19%. Harris and Hesterman[67] found that N uptake by corn from alfalfa residues at East Lansing, MI was 19% when spring incorporated, but only 14% when fall incorporated. More alfalfa N remained in the soil at planting for spring-incorporated (75%) than for fall-incorporated residues (54%). Differences in N recovery due to incorporation date were not observed at a second location (Kellogg Biological Station, Hickory Corners, MI), where corn recovered 25% of the alfalfa N and 68% remained in the soil. A second-year crop of barley (*Hordeum vulgare* L.) recovered less than 1% of the initial alfalfa input at both sites. N losses at East Lansing were attributed primarily to denitrification because of above-normal rainfall and the poorly drained, fine-textured soil. At Hickory Corners, leaching was the suspected cause of residue N loss because the soil was coarse textured and well drained. In contrast, a Nebraska no-tillage study showed more than 95% recovery of soybean residue ^{15}N by the subsequent soybean crop.[68] Nitrogen recovery differences between these studies illustrate the climatic and soil influences on N transformations in the soil.

Nitrogen use efficiency estimates using ^{15}N methodologies can be influenced by rate of N mineralization, differences in uptake of legume N among nonlegume species, or differences in methods used to determine recovery efficiencies. Exchange of ^{15}N for ^{14}N during mineralization-immobilization processes can result in low apparent recovery rates.[69] In addition to N effects, non-N contributions or rotation effects may influence interpretation of N contribution to a subsequent crop.[66]

Hargrove et al.[12] described N mineralization and decomposition patterns of leguminous residues as occurring in two distinct phases that could be described with a two-pool exponential model. One pool consisted of rapidly mineralized N from easily decomposable plant material that contained adequate N concentrations to meet the N demands of the decomposer community. The second pool of N had a slower mineralization rate and was probably composed of lignoproteins or lignin-protected N compounds that were less available to the decomposing microorganisms. Although N mineralization constants associated with the second pool indicated that mineralization continued after the readily mineralized N pool had been depleted, N release from the second pool was considered to reach an equilibrium with the simultaneous N immobilization that occurred throughout the decomposition process. Evidence of a significant portion of recalcitrant N remaining in residues was also offered by Ladd et al.,[65] who determined that residue N content reached a steady state after approximately 6 months.

B. Nonlegume Residues and Nitrogen Mineralization-Immobilization

Legume and nonlegume residues differ in decomposition and N mineralization rates due to the chemical composition of the residues. Nonlegume residues such as small grains, corn, and grain sorghum have larger C:N ratios (low N contents) that may require additions of exogenous N in order for decomposition to proceed.[70] These differences generally result in slower rates of residue decomposition for nonleguminous residues. Nonleguminous residues can affect soil N availability and subsequent crop production through microbial immobilization-mineralization of residue, fertilizer, and soil N. Nutrient immobilization, particularly N immobilization, is usually favored where residues with large C:N ratios are added to soil. Slower decomposition rates of surface residues result in a greater potential for immobilizing N for longer periods than for incorporated residues.[38] Residues from corn, grain sorghum, rice (*Oryza sativa* L.), wheat, and other small grains with large C:N ratios are noted for initial N immobilization.[51,68,71] Generally, mineralization of N from low-N residues occurs only after 50 to 60% is decomposed[27,72,73] or after the C:N ratio is below 30.

Residue management influences on N availability may be greater during initial phases of conversion from conventional tillage to no-tillage, particularly for low-input agricultural systems.[74] In Kentucky, Rice et al.[74] found that N availability in no-tillage and conventional tillage systems depended on the length of no-tillage management and amount of N applied to the system. When no N fertilizer was used, corn yields were greater in conventional tillage plots than in no-tillage plots during the first 9 years, but yields were approximately equal where high amounts of fertilizer N were applied. During the next 7 years, corn yields, response to N application, and availability of soil N showed little difference between the two tillage systems.

Standley et al.[41] found that loss of total N in a Vertisol in Queensland, Australia, during the fallow period tended to be greater where sorghum residues were removed and where disk tillage was used (Figure 4). Nitrogen losses from zero-tillage plots were mainly due to plant uptake, whereas NO_3^- leached below the 0.6-m sampling zone in cultivated plots.[75] Additional N losses were attributed to denitrification.

Residue placement influences N mineralization through an effect on the microclimate of the residue.[76,77] Christensen[72] observed a peak in net N immobilization after 8 months for incorporated barley residues, which was followed by net N mineralization. Surface-placed residues lost a small quantity of N during the first 30 days, probably due to leaching; this was followed by little change in residue N content. Holland and Coleman[24] found greater N immobilization and increased fungal abundance in wheat straw on the soil surface than in buried straw in Colorado. They estimated a greater N immobilization per unit litter loss and greater maximum net N immobilization in surface-placed straw. Increased N retention in surface residues was attributed to hyphal bridges that allowed fungi to use soil N and residue C. Conventional-tillage agroecosystems can be characterized as being bacterial-based food webs

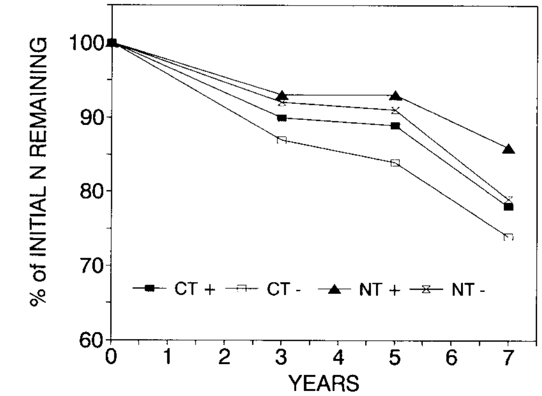

FIGURE 4. Relative change in soil total N at 0- to 0.1-m depth in a Vertisol during 7 years of conventional tillage (CT) and no-tillage (NT) with (+) and without (−) above-ground sorghum residues. (From Standley, J., Hunter, H. M., Thomas, G. A., Blight, G. W., and Webb, A. A., *Soil Tillage Res.*, 18, 367, 1990. With permission.)

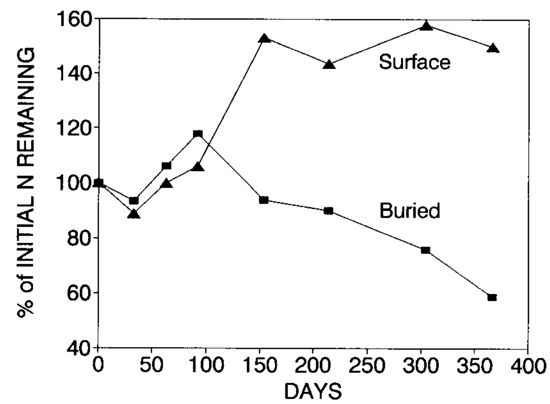

FIGURE 5. Nitrogen content of wheat residues on the soil surface or buried at Bushland, TX. Changes in N content indicate relative net immobilization or mineralization of N. (From Schomberg, H. H., Steiner, J. L., and Unger, P. W., *Soil Sci. Soc. Am. J.*, in press. With permission.)

with fast rates of litter decomposition and nutrient mineralization, while no-tillage agroecosystems, which accumulate residues on the soil surface, support fungal-based food webs that result in slower decomposition and greater nutrient retention.[78] Greater microbial biomass levels found near the soil surface in no-tillage systems have been related to greater immobilization of fertilizer N compared to conventional or shallow tillage practices.[37,74,79]

Placement of residues may play an important role in determining availability of soil N to subsequent crops during the N immobilization-mineralization process. Nitrogen content of decomposing wheat residues was influenced by placement at Bushland, TX (Figure 5).[80] Total N content of buried wheat residue increased initially until day 92 and then declined. Surface residue total N content increased gradually up to the fourth sampling (Day 153) with little change afterward. Estimates of microbial immobilization of N in surface-placed residues equaled 10.5 kg N/ha for grain sorghum residues and 14.6 kg N/ha for wheat residues after 1 year. In a wheat-sorghum-fallow cropping system, most of this N would be immobilized during the fallow period. However, net N mineralization might not occur during the following cropping season and would need to be accounted for when evaluating N requirements of the following crop.

Although greater N immobilization may occur with surface residues, subsequent N mineralization can occur within a period that is optimum for crop utilization. Nitrogen availability to wheat grown in the Pacific Northwest was similar from decomposing wheat residues either on the surface or incorporated, ranging from 8 to 11% of the total N applied in straw.[81] There was a trend for greater N recovery from no-tillage plots.

Slow rates of N mineralization from crop residues may improve the use efficiency of residue N for subsequent crops. Wagger et al.[82] examined N mineralization patterns from incorporated wheat and sorghum residues in continuous wheat and continuous sorghum systems in Kansas. After one cropping season, 12 to 15% of the wheat and 12 to 33% of the grain sorghum residue N was mineralized. The slow mineralization rate was beneficial in that the subsequent crop of wheat or sorghum recovered 79 and 82% of the mineralized N, respectively. Slower rates of N mineralization were observed for a very fine sandy loam compared to a silt loam for residues of both crops. Differences in mineralization rates between soils would have an impact on fertilizer N requirement of the subsequent crop and the potential for N loss due to leaching or denitrification.

Accumulation of N in high C:N ratio surface residues represents a potential temporary sink to reduce N loss from leaching. Immobilization of soil N within surface residues may have a positive influence on subsequent crop growth in that N remains near the root zone. However, leaching and denitrification losses of N within the soil profile may increase where surface-placed residues result in increased water infiltration and reduced evaporation rates.

Leaching and denitrification may be responsible for 20% or more loss of fertilizer N under some environmental conditions.[38] Denitrification losses of N from soil can be influenced by residue N content. Aulakh et al.[83] investigated the role of residues in loss of N due to denitrification in a loam soil (Aquic Hapludoll) in Nebraska. Corn, soybean, wheat, and vetch (*Vicia villosa* Roth.) residues with C:N ratios of 8 to 82 were placed on the surface or incorporated into repacked cores. Denitrification losses of N from the soil were negligible at 60% water-filled pore space. At 90% water-filled pore space, 87 to 127% of initial soil NO_3^- was lost due to denitrification and losses increased with increasing residue N content. Denitrification rates were three to four times greater for the legumes than for corn or wheat during the first 5 days. Initial N losses were less for surface residues, but no differences between crops were observed after 35 days.

V. RESIDUE MANAGEMENT EFFECTS ON PHOSPHORUS AND pH

As indicated above, no-tillage crop production usually results in an accumulation of plant residues on the soil surface and a redistribution of extractable nutrients with greater concentrations near the soil surface as compared to conventional tillage.[45,51,58,84] Conventional tillage mixes the soil, residues, fertilizer, and lime within the plow layer and creates a relatively homogeneous soil. The contrasting chemical and physical environments between conventional and no-tillage soils alter patterns of root growth, with no-tillage soils having greater root density near the soil surface, but lesser root density below 15 cm.[58] Although surface accumulation of nutrients and shallower distribution of roots occur in no-tillage systems, nutrient use by plants and crop yield can be equal to or greater than those observed in conventional tillage systems.[58,85,86] Residue management influences nutrient distribution and availability through microbial immobilization of nutrients in microbial biomass or organic forms, which can improve long-term nutrient availability by reducing nutrient fixation in unavailable inorganic forms.[87]

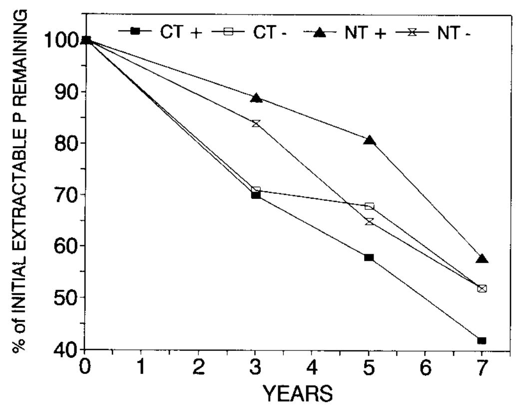

FIGURE 6. Relative change in soil bicarbonate extractable P at 0- to 0.1-m depth in a Vertisol during 7 years of conventional tillage (CT) and no-tillage (NT) with (+) and without (−) above-ground sorghum residues. (From Standley, J., Hunter, H. M., Thomas, G. A., Blight, G. W., and Webb, A. A., *Soil Tillage Res.,* 18, 367, 1990. With permission.)

A. Phosphorus

Phosphorus mineralization from crop residues is determined by the rate of residue decomposition and microbial immobilization of P.[87,88] In general, net immobilization of P occurs following addition of crop residues with less than 0.2 to 0.3% P, while net mineralization will occur with higher P contents.[88] During early stages of residue decomposition, net immobilization of P can conserve a substantial amount of P in slowly available organic forms. Organic matter mineralization and activity of enzymes (phosphatases) that mineralize P are influenced by the same factors that affect microbial activity, such as temperature, water, and pH. Cycling of P in soil is not easily measured, since mineralized phosphate may be removed from the soil solution via adsorption to colloidal surfaces or precipitation as Ca, iron (Fe), or aluminum (Al) phosphates, or immobilized into organic P.[88] Availability of P to plants is, therefore, a function of organic matter turnover, concentration of inorganic P in solution, and P requirements of microorganisms.

Standley et al.[41] observed that initial decreases in bicarbonate-extractable P in a Vertisol in Queensland, Australia were lower in no-tillage plots where grain sorghum stubble remained on the surface (Figure 6). During the first 3 years, no-tillage plots had significantly greater bicarbonate-extractable P. However, after 7 years, no significant effects of residue management practices on bicarbonate-extractable P were detected. Work by Saffigna et al.[89] on soil taken from the same plots indicated that 40 to 60% more microbial biomass P was present where stubble was retained.

Studies by McLaughlin et al.[90-92] indicate that crop residue P may not significantly contribute to the nutrition of a subsequent crop, but becomes incorporated into organic forms of P. They evaluated availability of ^{32}P-labeled fertilizer and ^{33}P-labeled medic (*Medicago truncatula* L. cv. Paraggio) residues to wheat. Wheat uptake of fertilizer P increased during the growing period and accounted for 11.6% of that applied. Little fertilizer P was found in microbial biomass or soil organic P fractions. Only 5.4% of medic residue P was recovered by wheat plants, and 22 to 28% was recovered in microbial biomass. After 95 days, the proportions of P derived from residue and fertilizer were approximately 9 and 18%, respectively, with the rest derived from soil. Most of the ^{33}P from medic residues was recovered in the inorganic P fraction at the beginning of the study, but almost 40% had been incorporated into organic P

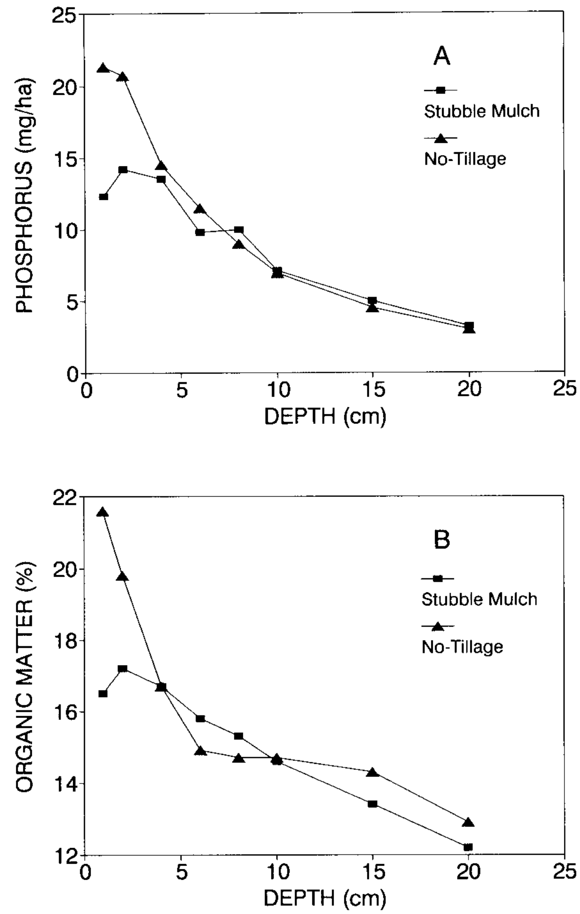

FIGURE 7. Soil P (A) and organic C (B) contents of Torrertic Paleustoll soil profiles after 6 years of no-tillage and stubble mulch tillage management at Bushland, TX. (From Unger, P. W., *Agron. J.*, 83, 186, 1991. With permission.)

fractions 5 days following application of residues to the soil. Medic P was unavailable for wheat growth because rapid release of P from medic residues occurred during a period when the wheat was still young. A major portion of medic P in soil was in organic fractions of microbial origin, indicating that residue P was mainly a source of inorganic P for microbial growth and synthesis of organic P. The microbial biomass, therefore, controlled the rate of organic P accumulation[93] and determined P availability from the medic residues.[94] However, McLaughlin et al.[92] pointed out that the relative contribution of crop residue P to the subsequent crop depended on availability of other forms of P and would be greater in a low P status soil.

Organic matter accumulation in the surface of no-tillage soils has been shown to influence P distribution.[57,58,84,95] For a wheat-sorghum-fallow system, extractable P was greater in the upper 0 to 2 cm of no-tillage soil than in stubble-mulch-tilled soil and declined in both soils below this depth (Figure 7A).[84] Comparing Figures 7A and B indicates that the decline in P in both soils at lower depths was closely associated with the decline in organic matter with depth. In Ohio, Dick[43] observed a trend for greater organic P accumulation between 2.5 and 15 cm in a silt loam and a silty clay loam under no-tillage compared to conventional and mulch tillage. Dick[43] suggested that the accumulation in this zone might have resulted from movement of organic P from the surface into the soil profile. Tiessen et al.[96] found that extractable PO_4-P concentrations were greater in the 0- to 5-cm layer with no-tillage compared to plow tillage in a fine silty loam in Nebraska. Below the 5-cm depth, P concentration was equivalent for the two tillages. Weil et al.[97] postulated that differences observed in distribution of inorganic forms of P between conventional tillage and no-tillage managed plots in three Maryland soils might be due to increased levels of organic matter in no-tillage surface soils. Greater quantities of organic material could increase P availability by shielding P adsorption sites on soil colloids. Additionally, surface application and reduced mixing of P fertilizer in no-tillage systems may reduce P fixation, thus allowing the accumulation of unreacted phosphate under no-tillage conditions.

Accumulation of crop residues and maintenance of organic matter are key factors in sustaining soil fertility. In Great Plains soils of Nebraska, Follett and Peterson[95] showed that adoption of no-tillage instead of stubble mulch or moldboard plow tillage helped to maintain fertility of the topsoil nearer to that of native prairie sod. After 16 years of alternate wheat-fallow cropping of soil previously in native sod, tillage had no effect on available P, while total P and organic P decreased from sod to plow in order of increased soil disturbance and decreased soil cover. A second site had been cropped from 1930 to 1959 and was reseeded to sod until 1969, when it was moldboard plowed and the alternate wheat-fallow rotation was begun. At this site, available P in the upper soil layers (0 to 5 cm and 5 to 10 cm) decreased in association with moldboard plowing and N fertilization. Accumulation of available P in the 0- to 5-cm portion of the no-tillage soil layer was attributed to the absence of mixing of applied fertilizer P. Nitrogen fertilization increased accumulation of total and organic P in the 0- to 5-cm depth, but there was a depletion of available and total P in the 5- to 10-cm depth. Tillage and fertility management, therefore, resulted in a redistribution of P into different forms and within the soil profile. Maintenance of surface residues in no-tillage appeared to retain or possibly increase the organic P fraction near the soil surface.[95]

Hargrove[58] determined that corn plants were smaller and P uptake was less with conventional tillage than with no-tillage. Using rubidium (Rb) to monitor nutrient uptake at different soil depths indicated that rooting and nutrient and water uptake were greater between rows and at greater depths with no-tillage. An evaluation of the soil profile showed a greater proliferation of roots near the soil surface and between rows of no-tillage plots. The Rb uptake, plant nutrient accumulation, and yield results indicated that redistribution of nutrients within the soil profile did not limit crop production with no-tillage compared to conventional tillage.

Residue management plays an important role in determining distribution and availability of P in cropped soils. Microbial activity, climatic factors, and soil chemical status all influence cycling of P in soil. Greater P availability in upper layers of no-tillage soils is apparently due to reduced mixing of fertilizer P, increased quantities of organic P, and a possible shielding of P adsorption sites. Future research on residue influences on P availability to plants should consider changes in organic P, microbial P, and inorganic P transformations in soil. Continued research on interactions between these pools should help improve efficient utilization of P in cropping systems.

B. pH

Changes in soil pH noted with adoption of no-tillage residue management are usually associated with lime, fertilizer, or tillage effects.[45] Residues have very little direct effect on soil pH. Data from Morachan et al.[98] indicate that, after application of corn stubble at 8 and 16 Mg/ha for 13 years on a sandy clay loam (Typic Hapludoll) in Iowa, soil pH declined 0.2 and 0.5 units, respectively. Application of alfalfa residue at 4 Mg/ha during this same period had no effect on pH, but a decrease of 0.2 units occurred with 16 Mg/ha of applied alfalfa. Longer-term application of large amounts of residues could result in decreased crop production if control measures are not implemented.

Observed decreases in pH have usually been attributed to use of ammonium nitrate fertilizer and are particularly noticeable on low base status soils in the southeastern U.S.,[99] but decreases have also been observed in Great Plains[95] and Pacific Northwest soils.[100] The absence of soil mixing following fertilizer application with no-tillage generally results in an increase in soil acidity, at least at the soil surface, while the pH of lower soil layers may change very little when compared to conventionally tilled soil. In no-tillage systems where lime is applied to offset this acidity, soil pH will increase near the soil surface, but may remain the same or continue to decline at a slower rate at lower depths.

Blevins et al.[45] found that after 10 years of lime application, soil pH at 0 to 5 cm was similar in no-tillage and conventional tillage plots, but without lime, pH was 0.5 or more units lower in no-tillage soil. Application of mineral N further decreased soil pH under both tillage systems. Tillage and N rate also influenced pH at 5 to 15 cm and 15 to 30 cm, but differences were smaller. They concluded that lime application to the surface of no-tillage soils was sufficient to overcome soil acidity. Dick[43] showed similar results for two soils in Ohio, where soil profiles (0 to 22.5 cm) were 0.1 to 0.3 pH units lower under no-tillage than under minimum and conventional tillage after nearly 20 years.

No-tillage management, including lime application, of a Typic Hapludult soil in Georgia resulted in a surface soil pH similar to that observed under conventional tillage for double-cropped wheat and soybeans[51] and for corn and rye cover crops.[58] Soil pH below 7.5 cm, however, decreased with depth in no-tillage plots, while conventional tillage plots had more homogeneous distributions of pH. Limited effectiveness of surface-applied lime in ameliorating pH problems deeper in the soil with no-tillage could limit depth of rooting, particularly on strongly acidic soils of low base status.

Exchangeable Al and Mn can become a problem in many soils as pH declines. Blevins et al.[45] noted that, in nonlimed no-tillage soil, exchangeable Al increased at 0- to 5-cm and 5- to 15-cm depths with N applications greater than 84 kg/ha, but remained relatively low in conventional tillage soil. Over 10 years, exchangeable Al essentially doubled in the no-tillage system. Blevins et al.[99] point out that leaching of Ca from soils in the southeastern U.S. contributes to lower pH and increased exchangeable Al, and this effect is greater for soils under no-tillage management. Studies in Kentucky indicate a certain amount of protection from Al due to increased organic matter in no-tillage soil.[101] Exchangeable Al activity in acid soils is reduced by the formation of Al-organic matter complexes.[102] The protective effect of organic matter on Mn toxicity is much less because organic matter does not complex with Mn as strongly.

Cropping of a native sod in Nebraska resulted in a decrease in soil pH compared to sod soil regardless of tillage method.[95] The pH declined through the 0- to 20-cm soil profile. Follett and Peterson[95] proposed that pH differences were the result of contrasting patterns of ion uptake in wheat-fallow as compared to sod. In a comparison of winter annual cover crops, Hargrove[64] found that soil pH was lower at 0- to 7.5-cm and 7.5- to 15.0-cm depths after growing legume cover crops than with fallow or rye.

In contrast to the above-noted decreases in pH with no-tillage, Juo and Lal[103] showed that pH of an Alfisol was similar under no-tillage and conventional tillage in Nigeria after 6 years. The no-tillage treatment maintained a significantly higher level of exchangeable Ca. This was attributed to increased exchange capacity associated with increased levels of organic matter and/or to decreased erosion with no-tillage. In Texas, Unger[84] found that pH at 0 to 20 cm of a Torrertic Paleustoll was not influenced by no-tillage and stubble mulch tillage. The pH at 0 to 1 cm for the stubble mulch soil tended to be greater, but this was not significant.

Cropping system influences on soil pH indirectly influence nutrient availability. Soil microorganisms are sensitive to acidic and alkaline conditions. Although decomposition of plant residues may not be influenced by pH values between 4.5 and 9.6,[104,105] other processes can be affected. Fu et al.[106] indicated that N mineralization increased as soil pH increased from 5 to 7. They noted a significant accumulation of NH_4^+ in one soil at pH 4. Mineralization of N in the presence of crop residues was greatly reduced at pH 4, and the effect was enhanced by addition of residues with large C:N ratios to the soil. Roper and Smith[105] found that the optimum pH for nitrogenase activity of free-living organisms was between 7 and 7.5 and was not related to the pH of the soil from which the organisms were isolated. Nitrogenase activity declined at pH levels outside the optimum.

The influence of residues on soil pH appears to be rather small, but method of residue management may greatly influence the soil reaction. Leaving residues on the soil surface to protect soils from wind or water erosion may necessitate added attention to changes in soil chemical properties, particularly in areas prone to pH-related problems under conventional tillage systems. Potential for pH changes with surface-managed residues is greatest in response to application of fertilizers or high-N residues to the surface and the absence of mixing soil amendments through the soil profile.

VI. SUMMARY AND CONCLUSION

Residue management can help improve soil productivity and crop production by maintaining soil organic matter levels. Two significant advantages of surface residue management are increased organic matter near the soil surface and enhanced nutrient retention. Greater microbial biomass near the soil surface acts as a reservoir for nutrients needed in crop production. In addition to the altered nutrient distribution within the soil profile, changes also occur in the chemical and physical properties of the soil. Root growth within this zone tends to increase, which results in improved nutrient and water use efficiency.

Nutrient management in reduced-tillage systems may become more difficult due to changes in soil physical properties that influence microbial activity and mineralization of nutrients. During the transition from conventional tillage to no-tillage systems, a period may exist where nutrient availability is reduced and additional fertilizer applications may be required to attain yields equal to those previously achieved. On poorly drained soils or in cool, wet regions, reduced tillage and surface residues may delay and reduce microbial activity and crop growth, reduce yields, and increase N loss from denitrification or leaching.

Soil acidity problems appear to be greater in low base status soils and with application of acid-forming fertilizer. Lime application to the surface of no-tillage soils has been effective in offsetting soil pH problems, but some incorporation may be necessary under certain conditions. Long-term use of no-tillage practices will require greater attention to changes in soil properties associated with surface residues.

As continued emphasis is placed on environmentally sound agriculture, questions may be raised about the social, economic, and environmental consequences of using soil organic matter as a nutrient resource. Organic matter decline represents a potential loss of production because organic matter contributes to the nutrient and water holding capacity of a soil. Some soil degradation will occur with crop production unless residue production is great enough to offset organic matter loss; however, application of current knowledge on residue management can help reduce this effect. Improved residue management and reduced tillage practices should continue to be encouraged because of their beneficial role in reducing soil degradation, increasing soil productivity, and contributing to sustainable production.

VII. RESEARCH NEEDS

Progress has been made in understanding residue influences on soil organic matter and N availability. Recent research activities have focused on the use of isotopes for evaluating nutrient cycling through various soil pools, the importance of microbial biomass as a source and sink of nutrients, and long-term changes in soil properties due to tillage and cropping systems. These studies have provided great insight into soil processes influencing nutrient availability.

Increased efforts to model C, N, P, S, and other nutrient cycles in the soil have improved our understanding of the many physical, chemical, and biological processes that interact within agricultural ecosystems. A greater emphasis should be placed on multidiscipline approaches in modeling and the development of linkages between models. Research problems related to residue management should be carried out with consideration of potential modeling uses of data. Collection of additional data needed for model validation and exploration of alternate modeling scenarios could then help in understanding research results.

Some additional research needs are:

1. Evaluation of crops in terms of residue production, decomposition, and nutrient retention with the objective of improving organic matter inputs to soil.
2. Investigation of nutrient cycling within reduced tillage and residue management systems to provide a better understanding of changes in nutrient availability.
3. Determination of crop rotation influences on nutrient redistribution within the soil profile; are residues of deep-rooted crops important in redistribution of nutrients from within the soil profile?
4. Evaluation of crop residue effects on interactions between inorganic, organic, and microbial forms of P in the soil and subsequent P availability to plants.
5. Determination of the fate of nutrients other than N in reduced-tillage systems.
6. Investigation of residue and organic matter influences on nutrient availability in highly weathered soils.
7. Encouragement of the use of multidisciplinary approaches to problems associated with residue management.

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