Nutrient Stratification in No-till Soils

by John H. Grove, Raymond C. Ward, and Ray R. Weil

SCIENCE

Grove, Ward, and Weil are soil scientists at U. Kentucky, Ward Labs, and U. Maryland, respectively.

Editors' Note: Leading Edge *is privileged to publish this article by three of North America's most respected soil scientists. John Grove, Ph.D., has focused his applied field research program on chemical and physical management of no-till soils for the past quarter-century. Ray Ward, Ph.D., has developed several agricultural testing laboratories from South Dakota to Oklahoma, and has endeavored tirelessly to improve farmer and agronomist understanding of soils and crop nutrition. Ray Weil, Ph.D., is a professor at University of Maryland and has researched soil fertility for over 25 years in a state where no-till has become the convention. Weil is also the author of the textbook* The Nature and Properties of Soils, *14th Edition, Prentice Hall, 2008.*

Photo by Ray Weil.

No-till is becoming the standard practice in place like Pennsylvania. The heavy mulch improves the crop and the soil. But could the situation be improved further by deep placement of fertilizers?

Nutrient 'stratification' commonly refers to a distribution of nutrients that is non-uniform with soil depth, and especially to situations with higher concentrations of nutrients (such as phosphorus or potassium) near the soil surface. Nutrient stratification certainly does occur in agricultural soils, but is generally not a problem for plant nutrition, and is at times beneficial. Nutrient stratification has existed since soils began weathering and coming under the influence of terrestrial plants with roots. Nutrient stratification apparently was not an issue for the functioning or robustness of prairie or forest ecosystems, which endured and frequently prospered for thousands or even millions of years without any mechanism for redistributing nutrients other than biological processes and water percolation. However, in the minds of many agriculturalists the common assumption or implication is that soil nutrient stratification is inherently a negative attribute for crop production, and one which must be alleviated by deep fertilizer placement and/or tillage. This article will explore the evidence for or against this proposition, as well as reviewing the plant and soil processes involved in both the creation and mitigation of nutrient stratification.

Surface application of lime in no-till can raise soil pH at depths of 12 inches or more over periods of several years.

Stratification Concerns: Historical Context

When mechanized no-till cropping first got started in Virginia, Kentucky, and nearby regions in the 1960s and early '70s, we heard concerns about stratification of both nutrients and soil acidity (lower pH near the soil surface). Many agronomists worried that farmers would have to deep plow to periodically incorporate lime and fertilizer. Generally, these concerns never became reality.

For ameliorating soil acidity, many studies in no-till systems have demonstrated that surface application of lime (without mechanical incorporation) is highly effective. This is perhaps not so surprising because it is near the surface that soil is acidified by the actions of precipitation (which is typically acidic even when not influenced by human activities), ammonium oxidation, and decay of organic materials. Surface application of lime in no-till can also be effective in raising soil pH at depths up to 30 cm (12 inches) or more over periods of several years.[1] Percolating water and bioturbation move

[1] E.F. Caires, G. Barth & F.J. Garbuio, 2006, Lime application in the establishment of a no-till system for grain crop production in southern Brazil, *Soil & Tillage Res.* 89: 3-12. See also R.L. Blevins, L.W. Murdock & G.W. Thomas, 1978, Effect of lime application on no-tillage and conventionally tilled corn, *Agron. J.* 70: 322-326. W.W. Moschler, D.C. Martens, C.I. Rich & G.M. Shear, 1973, Comparative lime effects on continuous no-tillage and conventional tilled corn, *Agron. J.* 65: 781-783.

lime into no-till soils. Subsoil pH can be elevated more quickly with tillage incorporation of lime, although this can be very costly and destructive. These and other studies show that surface application of lime in no-tillage tends to produce the desired crop yield response as well as the best economic return.

Fertilizer placement (including deep placement) has been far more extensively studied than liming, apparently with greater expectation of positive results from overcoming nutrient stratification. However, the results have generally not shown favorable responses to alleviating nutrient stratification, as illustrated by early work in Kentucky (see Table 1). Moldboard plow and no-till plots, established in 1970, were incrementally sampled (to the depths indicated) in the fall of 1980 and 1981, and the results averaged in the table. Potassium (K) stratification was substantial, and more pronounced in the no-till soil, although total K was very similar when the increments were added to give a composite over the 0- to 12-inch depth. Potassium fertilizer was surface-applied at a rate of 180 lbs of 0-0-60 per acre each year (both years). In both 1980 and 1981, corn was sampled at physiological maturity and total K uptake determined. Averaged over two years, the uptake of K by no-till corn was 130% of the corn grown on plowed soils, which coincides with the observation that the no-till soil test K was 129% of plowed soil test K, but only in the surface 2 inches of soil (*total* or composite soil test K for 0 to 12 inches was nearly identical between plowed and no-tillage). This strongly suggests that the K nutrition of these two corn crops was *improved* by K stratification.

While plowing has declined in popularity across much of North America, the concern about nutrient stratification is more at the forefront than ever. There has been a recent surge of interest in deep fertilizer placement (without full-width tillage), often termed 'strip-till' or 'zone-till.' (Note, however, that strip-till is occasionally done without fertilizer placement, as a method of warming and/or drying the intended row area, or otherwise aiding planter performance.) Let's look at the science to see if any validity can be found in these methods and theories on deep placement.

Other Research on Nutrient Distribution

In Iowa, José Bordoli and Antonio Mallarino studied P and K placement (deep vs. shallow vs. surface) for corn from 1994 to 1996 at numerous locations for a total of 26 site-years.[2] Sites varied in soil test levels (including some low and very low P values), degree of stratification, and length of time under no-till management (some up to 9 years). All sites were in a corn >>soybean rotation. While some sites were responsive to applied P, there was *no* significant ($P \leq 0.05$) response *to placement* at any site. Several sites were responsive to K application, but only one site-year showed a significant response to K *placement*. When all sites were pooled, a significant positive yield response to K placement was observed, averaging about 2%. However, the authors concluded that "yield differences would not offset higher application costs [for deep-placed K fertilizers]."

At two locations in southern Ontario over a period of years from 1995 to 1998, Tony Vyn and Ken Janovicek were also studying K placement for corn.[3] Locations had been in no-till for at least 6 years when the studies commenced. The corn crops in the study were planted into wheat stubble. While the sites were generally responsive to K application, corn yields tended to be maximized with planter-applied K fertilizer in a '2 by 2' side-band (2x2, i.e., a band 2 inches beside and 2 inches below the seed)[4] rather than by deeper applications the previous fall.

Table 1. Distribution of Soil K and Corn Uptake in Two Tillage Systems in Kentucky

Soil test K: Increment			Soil test K: Composite				Corn K Uptake	
Depth: increment, inches	no-till (NT)	moldboard plow (MP)	Depth: composite, inches	no-till (NT)	moldboard plow (MP)	ratio NT/MP	year	ratio NT/MP
	ppm K			ppm K				
0 to 2	170	132	0 to 2	170	132	1.29	1980	1.35
2 to 6	104	113	0 to 6	126	119	1.06	1981	1.25
6 to 12	86	95	0 to 12	105	107	0.99	Avg.	1.30

In this study, K stratification in long-term no-till actually enhanced corn uptake as compared to plow tillage. Plot tillage systems had been in place for 10 years at beginning of study. K soil test was by neutral ammonium acetate extraction. Source: R.L. Blevins, J.H. Grove & B.K. Kitur, 1986, Nutrient uptake of corn grown using moldboard plow or no-tillage soil management, *Commun. Soil Sci. Plant Anal.* 17: 401-417.

2 J.M. Bordoli & A.P. Mallarino, 1998, Deep and Shallow Banding of Phosphorus and Potassium as Alternatives to Broadcast Fertilization for No-till Corn, *Agron. J.* 90: 27-33.

3 T.J. Vyn & K.J. Janovicek, 2001, Potassium Placement and Tillage System Effects on Corn Response following Long-Term No Till, *Agron. J.* 93: 487-495.

4 *Editors' Note: With tillage, it was considered important to be 2 inches below the seed as well as 2 inches laterally because the soil was dried by tillage and roots didn't grow well near the surface. In no-till, it has been repeatedly demonstrated that placing the side-band at approximately the same depth as the seed is perfectly acceptable agronomically as well as reducing horsepower and down-pressure requirements. For various reasons, no-till producers often move the opener farther laterally from the row. This is most accurately described as '3x0' or '4x0.'*

At a different location in southern Ontario in 1997 & 1998, Vyn and fellow researchers found positive corn yield responses to K fertilization in fields that had more than a decade of no-till history, but with results pooled, no response occurred for deep placement of K in no-till and zone-till plots as compared with shallow placement.[5]

While many studies found advantages to subsurface application of P and K, the idea that deeper placement is better than shallow has generally not been substantiated by the evidence.

Another study at Purdue University and conducted by Vyn's graduate student, Ann Kline, again could find no response to deep placement of P and K fertilizers for corn.[6] Averaged across 2 years and 2 hybrids, deep placement provided no yield benefit over broadcast fertilizer.

Previous studies by various scientists produced results prompting similar conclusions: Shallow planter side-band applications were as good if not better than deep placement for efficiently fertilizing corn.[7] While these and many other studies found advantages to subsurface application of P and K, the idea that deeper placement is better than shallow has generally not been substantiated by the evidence.

For soybean, Xinhua Yin and Tony Vyn looked at the effect of K placement (deep vs. shallow vs. surface) at two locations from 1998 to 2000 (6 site-years) in Ontario.[8] Once again, shallow placement and surface broadcast tended to outyield deep placement. They concluded that "soil K stratification and the residual effects of tillage and K placement were not major production issues for NT [no-till] soybean production."

An exhaustive study by Rogerio Borges and Antonio Mallarino involved different P and K placement strategies for soybean over 31 site-years (20 site-years at university research farms; 11 site-years of short-term trials established in producers' fields).[9] Pooling all the site-years, they found only a slight yield response to P application, and *no* response to placement. K application also resulted in a slight yield advantage, and placement effects were very subtle—less than a 1% yield advantage to deep placement over planter side-band when the 20 site-years were pooled. Other studies have produced similar findings.[10] Although nutrient stratification in many soils is well-documented, and theories for alleviating it abound, positive crop yield responses to deep placement of fertilizers are almost nil despite extensive studies looking for this effect.

As the foregoing studies tend to demonstrate, deep placement into a nutrient-stratified soil may actually be detrimental for crop uptake, and especially so when the soil is medium-low in overall nutrient availability. This is further verified by some recent Kansas work reported by Greg Schwab et al.[11] Three locations in southeast Kansas (all in Bourbon County) were studied for three years in various sequences of corn, grain sorghum, soybean, and wheat. These fields averaged 11 to 16 ppm Bray P-1 for the 0- to 6-inch depth, with P values 2-fold to 5-fold higher in the surface 0 – 2 inches compared to the deeper 2 – 6 inches (the sites were deliberately chosen for their P stratification and reduced-tillage history). Tillage and no-tillage treatments at the sites were further subdivided into four fertilizer P treatments: no P

Positive crop yield responses to deep placement of fertilizers are almost nil despite extensive studies looking for this effect.

---

5 T.J. Vyn, D.M. Galic & K.J. Janovicek, 2002, Corn response to potassium placement in conservation tillage, *Soil & Tillage Res*. 67: 159-169.

6 http://www.agry.purdue.edu/staffbio/KlineMSThesis2005.pdf

7 D.B. Mengel, S.E. Hawkins & P. Walker, 1988, Phosphorus and potassium placement for no-till and spring plowed corn, *J. Fert. Issues* 5: 31-36. B.G. Farber & P.E. Fixen, 1986, Phosphorus response of late planted corn in three tillage systems, *J. Fert. Issues*, 3: 46-51. See also G.W. Randall & R.G. Hoeft, 1988, Placement Methods for Improved Efficiency of P and K Fertilizers: A review, *J. Prod. Agric*. 1: 70-79. (In reviewing a number of pre-1987 studies, Randall and Hoeft found that deep placement seldom conferred a yield advantage over shallow or surface placement for corn and soybeans. Yields from planter side-band placement of P and/or K generally equaled or exceeded those from deep placement. The only studies finding advantages to deep placement were comparing to surface applications only, not shallow placement as with a planter side-band.)

8 X. Yin & T.J. Vyn, 2002a, Soybean Responses to Potassium Placement and Tillage Alternatives following No-till, *Agron. J.* 94: 1367-1374. A similar set of studies by Yin & Vyn found no significant response of soybean yield to tillage method or residual fertilizer placement from the previous corn crop. X. Yin & T.J. Vyn, 2002b, Residual Effects of Potassium Placement and Tillage Systems for Corn on Subsequent No-Till Soybean, *Agron. J.* 94: 1112-1119.

9 R. Borges & A.P. Mallarino, 2000, Grain Yield, Early Growth, and Nutrient Uptake of No-Till Soybean as Affected by Phosphorus and Potassium Placement, *Agron. J.* 92: 380-388.

10 C. Hudak, R. Stehouwer & J. Johnson, 1989, An evaluation of K rate, placement and tillage systems for soybeans, *J. Fert. Issues* 6: 25-31. (The study found that placing K in narrow bands increased soybean yield for both surface and deep placement.) See also Randall & Hoeft, 1988.

11 G.J. Schwab, D.A. Whitney, G.L. Kilgore & D.W. Sweeney, 2006, Tillage and Phosphorus Management Effects on Crop Production in Soils with Phosphorus Stratification, *Agron. J.* 98: 430-435.

Table 2. Bray P-1 (ppm P) by Depth after 20 Years of Tillage or No-till. Rogers Memorial Farm, Nebraska, fall of 2000.

Soil Depth	Fall Plow +Disk +Disk	Fall Chisel +Disk	Spring Disk (twice)	Spring Disk (once)	No-till
0 – 2″	14.3	24.5	27.0	27.7	46.1
2 – 4″	12.4	14.9	10.3	11.4	14.2
4 – 6″	12.1	9.1	5.7	6.4	8.9
6 – 8″	11.3	6.1	5.7	5.4	6.8
Avg.	12.5	13.7	12.2	12.7	19.0

Extractable phosphorus for five tillage systems (3 replications each) that had been in place continuously for 20 years during which no P fertilizers were applied. Source: Paul Jasa, personal communication Dec. 2006.

Table 3. Bray P-1 (ppm P) by Depth for Tillage Study at Rogers Memorial Farm, NE, fall of 2004.

Soil Depth	Fall Plow +Disk +Disk	Fall Chisel + Disk	Spring Disk (twice)	Spring Disk (once)	No-till
0 – 2″	25.5	46.1	62.6	64.9	75.9
2 – 4″	26.2	36.6	45.3	29.1	34.4
4 – 6″	21.8	13.3	11.6	11.8	11.7
6 – 8″	17.9	8.3	7.7	8.3	10.0
Avg.	22.8	26.1	31.8	28.5	33.0

Same study as Table 2, but 4 years later. After soil sampling in the fall of 2000, fertilizer was broadcast at 100 lbs/a of P_20_5 on all plots prior to fall tillage treatments. Source: Paul Jasa, personal communication Dec. 2006.

Table 4. Multi-Year (1995–2000) Average Soybean & Sorghum Yields (bu/a) for Tillage Study at Rogers Memorial Farm, Nebraska.

	Fall Plow +Disk +Disk	Fall Chisel +Disk	Spring Disk (twice)	Spring Disk (once)	No-till
Soybean	42.8	46.8	46.2	48.4	51.3
Sorghum	96.4	98.8	93.6	104.5	109.5

Same study as Tables 2 and 3. Source: Paul Jasa, personal communication Dec. 2006.

added; 40 lbs/a of P_2O_5 applied 6 inches under the row before planting; in a 2x2 band at planting; and, surface broadcast prior to tillage, if any. Subsurface P placement (either by 2x2 or deep-banding 6 inches below the row) improved early crop growth and P uptake about 50% of the time, but positively influenced yields only 25% of the time. As with some other studies discussed, the planter side-band often provided greatly improved P uptake at V6 growth stage for both corn and sorghum as compared to other treatments (including deep placement), although there was little relationship between early plant growth and/or P uptake responses and the final grain yield response for any of the treatments.

Further insight can be gained from a set of long-term tillage plots that has been in place since 1981 near Lincoln, Nebraska, under the care of Paul Jasa (UNL Extension Agricultural Engineer), located on an upland silty clay loam soil. No phosphorus was applied until 2000, just after the first incremental-depth soil sampling. The Bray P-1 extractable P values are reported in Table 2. Phosphorus distribution with depth was similar for fall chisel + disk, spring disk, and no-till regimes.

After samples were taken, 100 lbs/a of P_2O_5 was broadcast on the surface of all plots as 192 lbs/a of 11-52-0 late in the fall of 2000. After 4 crop-years in a grain sorghum >>soybean rotation, incremental-depth soil sampling was repeated in the fall of 2004, and the Bray P-1 extractable P values are reported in Table 3.

Jasa commented in 2002, with soil test results similar to those presented in Table 3: "No-till 'adjusted' P levels deeper into the soil than disking 4 times over 2 years. When looking below the surface layer, stratification is less of a problem with no-till than with the disk systems."[12] The effect persisted, as Table 3 shows: After disking 8 times in 4 years, the P distribution was still no better than no-till.

Another aspect of these UNL data is the higher soil test P values (average) under no-till. One possible explanation would be reduced no-till yields and associated lower P removal in grain. However, yield results show a distinct long-term no-till yield advantage (see Table 4).

A more plausible mechanism for causing the higher P values in the no-till plots involves the greater concentrations of P and organic matter at the soil surface. These will tend to reduce net P 'fixation' (the sorption onto soil particle edges and formation of insoluble compounds which render the P unavailable to crop roots and other soil organisms). The reduced mixing of P in no-till soils allows the greater soluble P concentrations to 'swamp' the finite number of P-fixation sites, reducing the soil's P buffer capacity, and thereby increasing the plant-available P. Certain organic compounds bind to various cations (calcium, aluminum, and iron) located at these fixation sites, preventing the formation of P-fixing compounds. In other words, shallow placement of P fertilizers in no-till can and does provide an efficient supply of this nutrient to crops under the old rule: "Minimize P contact with the soil, but maximize P contact with roots."[13]

Proponents of deep placement often worry that crop nutrient uptake will be poor in drought years if nutrients are concentrated in dry upper soil layers. However, this

[12] Paul Jasa, personal communication Dec. 2006.

[13] Yet another possible explanation for the greater P values in the UNL no-till plots is the greatly reduced runoff and erosion in those as compared to the tillage plots (the site was on upland soils.) Many studies show that P loss via soil erosion is substantial when tillage is done. As important as this may be, the authors suspect that biological processes in no-till are likely the primary contributor to increased P soil test values. See Figure 1.

Photo by Brian Lindley.

Even in semiarid climates during the worst drought on record, crops still produce many roots near the surface in continuous no-till with good mulch. The photo shows proso millet roots at Gabe Brown's near Bismarck, ND in '06. Every small rain shower moistens the soil near the surface, allowing renewed root growth and nutrient uptake. Meanwhile, the subsoil becomes drier and drier. Shallow nutrient placement works well in continuous no-till.

is not borne out by research results. For instance, in the Nebraska study, the summer of 2006 was considerably drier than normal, yet the yield advantage to the no-till system persisted despite the nutrient stratification (see Table 5).

However, the argument will be made that preserving the majority of crop residues on the soil surface *plus* deep placement of P and/or K (via strip-till or zone-till), could be beneficial to grain yield if dry weather occurs during rapid vegetative growth. The Bordoli and Mallarino corn study found a correlation of greater relative K-placement yield response with drier June weather, although the relative response comparison discussed was between deep-banded K and *broadcast* K. Bordoli and Mallarino did not discuss the relative response of deep K to planter side-band K as being correlated to drier June weather—presumably there was less correlation, or none. Other studies tend to show little, if any, positive yield response to deep placement of nutrients with strip-till or zone-till (with residues retained between the strips) as compared to no-till with shallow nutrient placement, even in dry growing seasons.[14]

Table 5. Soybean & Sorghum Yield in 2006 for Tillage Study at Rogers Memorial Farm, NE.

	bu/a	
	Soybean	Sorghum
Plow +disk +disk	43.2	92.1
Chisel +disk	55.7	90.2
Disk +disk	56.2	90.1
Disk	58.9	91.3
No-till	62.0	99.6

Source: Paul Jasa, personal communication, Dec. 2006.

Deep mechanical nutrient placement has additional drawbacks. Both fixed and variable costs are greater. Leaching losses of nutrients may be substantial for some soil types and climates. Moisture losses associated with residue movement and degradation in the row area may impede uniform seed germination and plant emergence in dry years. Erosion (and nutrient losses in runoff) will be increased with strip-till or zone-till on slopes. While many studies find increased early growth of crops planted over the tilled and fertilized strips or zones, often along with increased P and/or K uptake in the plant tissues, there is typically little relationship between early plant growth (and P and/or K uptake responses) and final grain yields in those studies.[15]

Studies tend to show little, if any, positive yield response to deep placement of nutrients with strip-till or zone-till (with residues retained between the strips) as compared to no-till with shallow nutrient placement, even in dry growing seasons.

The only real downside to nutrient stratification that has been consistently observed is that more dissolved P (both organic and inorganic) may be lost in surface runoff water. This is usually far less of a problem than the P lost in sediments eroded from tilled soils.

Normal Plant/Soil Relationships (Long-Term Nutrient Cycling)

Plants themselves move nutrients within their tissues (that's why they're called *vascular* plants: because of

[14] See Vyn et al., 2002. (During the dry season of the study, 1998, the deep banding actually caused substantial yield *reduction* in the no-till plots. Pooling the zone-till and no-till treatments for that year, there was still a slight disadvantage to deep placement.) See also Vyn & Janovicek, 2001, which included a dry season. See also Paul Fixen's study on dryland corn in South Dakota, which also found that planter 2x2 placement outyielded other treatments including deep placement, regardless of tillage system, as reported in Randall & Hoeft, 1988. (*Editors: For another example, see the data tables in 'Another Look at Strip-Till' in the Dec. '05* Leading Edge.)

[15] The occasional differences in grain yield found in these studies likely are not due to fertilizer placement so much as other mechanical and physiological factors, such as plant population disparities, advancing or retarding crop development with coincidental weather effects, etc. When multiple years and locations are pooled from these studies, yield differences due to fertilizer placement and/or in-row tillage practices tend to disappear.

Photo by Ray Ward.

Native ecosystems, such as this grassland in south-central Nebraska, thrived for millions of years with nutrient-stratified soils. Indeed, the stratification likely slowed leaching losses of nutrients, conferring a benefit.

large-scale transport of fluids and dissolved substances by specialized conductive tissues). The majority of the N, P, K, and other nutrients will be moving from the roots to the leaves and stems, which eventually die and fall onto the soil surface to decompose. This is how most stratification occurs under indigenous non-fertilized ecosystems, as well as in cropland. Intensive cropping, especially with deep-rooted species and cover crops, will accelerate nutrient pumping from greater depths and actually enhance stratification (see Figure 1). Nature relies on such mechanisms to keep nutrients from leaching below the rooting zone. Numerous biological and climatic influences then operate to redistribute nutrients from areas of high concentration (such as upper soil layers) to areas of lower concentration (e.g., at depth).

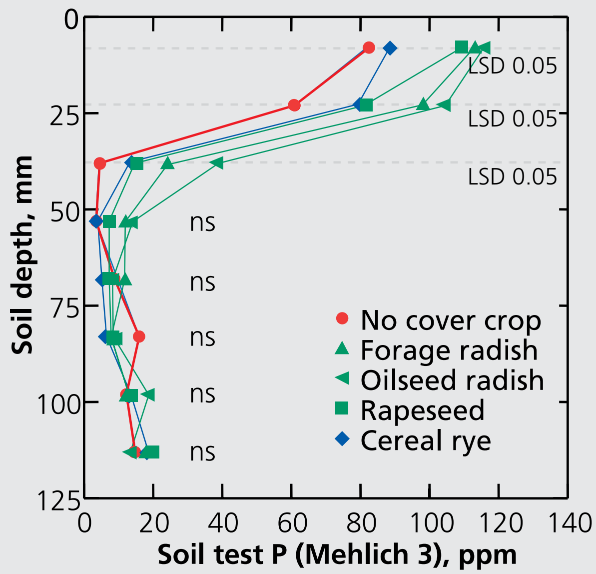

Figure 1. Cover crops enhance natural stratification by bringing nutrients up from deeper layers and making them more available for crops in the surface soil. This Maryland coastal plain soil (silt loam) has been cropped for over a century, with the last 6 years under low-disturbance no-till in a corn >>soybean rotation. Only the last 3 years with the cover-crop treatments are presented (graph values are 3-yr averages). The dramatic long-term stratification of soil P is enhanced by the cover crops, especially the radishes. These plants not only bring up P from deeper layers and deposit it (via their residues) at the surface, but also their roots excrete organic acids that make soil P more available to plants. Before a killing freeze in December, the radish tissues contained very high P concentrations, averaging 0.6% P. (Source: Unpublished data from Weil and graduate students.)

Plants have evolved to cope with the resulting nutrient stratification, with the ability to produce extensive root mass in the volume of soil near the surface. This especially happens in no-till systems with abundant surface mulch, which tends to maintain sufficient moisture beneath the mulch for crop root growth during much of the season. (Uptake of some nutrients only occurs at the root tips, which must be actively growing.)

Further, the plant's roots are extremely adaptive, responding to areas of higher nutrient availability by causing root growth to proliferate there, so long as conditions remain suitable for nutrient uptake at that location. (*Editors: See 'Roots: The Foundation' by Rick Waldren in the March '06 issue.*) Finally, an undisturbed soil covered by plant residues encourages the formation of mycorrhizae, the beneficial association of certain fungi with roots that enormously enhances the nutrient-gathering ability of many crop plants.

Four things needed for root uptake: the nutrient, water, oxygen, and roots themselves, all in the same place at the same time. This occurs readily in soil biopores, unless mechanical disturbance interrupts them.

The four things that are needed for nutrient uptake by roots are: the nutrient (in a plant-available form), water, oxygen, and the roots themselves, all in the same place at the same time. Where you have poor (short) crop rotations, you typically have poor roots. For instance, in *Wheat Health Management*, Jim Cook and Roger Veseth discuss placing nutrients in a disturbed zone. The soil disturbance interrupted pathogenic *Rhizoctonia* hyphae, allowing root growth in the zone where the nutrients were placed. The roots did not use the whole soil mass, only the part where till-

Photo by Brian Lindley.

Healthy plants grow many fine roots, visible here. (This was corn in long-term no-till.) You would need magnification to see the mycorrhizal hyphae network.

age was done, because of *Rhizoctonia* diseases associated with monoculture or alternate-year wheat. As long as it rained enough (or rotations were very conservative), the disturbance plus fertilizer placement system was reasonably successful.

To take this somewhat further, consider ridge-tillage, where the plant row is located in the same place each year. Many studies were conducted to figure out how much extra fertilizer was needed to offset the management-induced problem of root pruning in this system. With ridge-till, plant growth extracts nutrients from beneath the ridge and cycles a portion to the row middles (where the residues fall). The roots from next year's crop grow from the ridge down to and under this mat of residue. The roots proliferate until the first cultivator pass, which both rebuilds the ridge and cuts off roots. The growing plant must then subsist on a reduced root mass which is located where nutrient concentrations are lower (under the ridge).

Prior to human intervention, virtually all terrestrial ecosystems exhibited considerable nutrient stratification. Although nutrients were more concentrated near the soil surface for millions of years, ecosystems didn't crash, and many became increasingly robust over millennia.

The differences between these scenarios and long-term low-disturbance no-till are considerable. When undisturbed, soil macropores are created by fauna and flora. Plants contain nutrients in their roots. When the roots decay, these nutrients are left behind in these biopores, which subsequent roots tend to follow. Earthworms do similar things. Their burrowing engulfs and mixes soil, adds uptake-enhancing enzymes (e.g., phosphatase), and deposits excreta with other characteristics that happen to be beneficial for plant uptake. Roots follow these channels as well. The roots do this primarily because it is an easier path, not because of greater nutrient availability. These macropores are higher in oxygen and they tend to conduct water deeper into the soil when they are continuous and open to the surface. When someone tills, uses high-disturbance seeding, heavy harrows, etc., they interrupt macropore openings to the surface, thus negating the macropore ability to conduct water during rainfall or irrigation. Subsequent precipitation washes disaggregated soil particles into the remnants of the pores, clogging them; oxygen is then less available in the macropore than the surrounding soil. Essentially all studies that have been conducted show that earthworms and other macrofauna are more abundant in undisturbed (no-till) soil. No-till's mulch cover also moderates soil temperatures and retains moisture to create conditions suitable for root growth near the surface during most of the season.

Prior to human intervention, virtually all terrestrial ecosystems exhibited considerable nutrient stratification. The foundation of land ecosystems is photosynthesis, which means that some plant tissues must be exposed to the sun, and are therefore aboveground. When these tissues die, they soon decay and the relinquished nutrients enter the upper portion of the soil. Hence, stratification. But ecosystems did not stall from nutrient deprivation, and indeed were relatively efficient at conserving nutrients over many eons. Infiltrating moisture would move dissolved nutrients downward in the soil profile at varying rates, depending on nutrient solubility, soil texture, etc. Earthworms, mycorrhizae, and vascular plants would redistribute the nutrients acquired from the upper portion of the soil profile. As herbivores fed on the aboveground plant material (and carnivores fed on the herbivores), their excrement again came to rest on the soil surface, which often was moved into the soil by dung beetles (and other fauna); the manure was mixed *in situ* with low-N carbon material and 'injected' just below the surface. As the herbivores (or carnivores) died and the carcasses came to rest on the soil surface, decay processes ensured that even the bones again reached soluble mineral status and moved into the soil. Although nutrients were more concentrated near the soil surface for millions of years, ecosystems didn't crash, and many became increasingly robust over millennia. *Stratification is normal*.

Returning to agriculture, some studies and experiences do find a favorable crop yield response allegedly due to

Photo by Roger Long.

Here, the soil-like clumps you see are actually nightcrawler poop, forming a midden around their permanent burrow home. In continuous no-till with abundant crop residues, earthworms will typically become prevalent and enhance soil nutrient availability for plants. Photo is from the irrigated portion of Dakota Lakes Research Farm (nightcrawlers were 'seeded' in the early '90s there).

'zone-building' or strip-till. In many of these reports, the response is to redistributing a compacted layer, or to N and/or P and/or K placement in proximity to a corn row, not the fact that the nutrients were placed at depth or that a certain implement was used to place them. These studies are usually not breakthroughs, often because of inadequate control treatments (what happened when the fertilizer was banded shallowly near the row but without the deep shank? what happened without the fertilizer when just the shank ran through the soil?). Several other factors can confound the results. If secondary nutrients (e.g., sulfur) or micronutrients (e.g., zinc) are limiting, the tillage done in the strip or zone may increase availability of those nutrients as soil organic matter is mineralized. Also, if the planter is not reasonably equipped to do an adequate job of placing seeds in the low-disturbance no-till plots, the study may be biased by an inadequate plant population and/or less uniform emergence. If crop rotations are unfavorable for low-disturbance no-till, such as being too low in water extraction, or previous crop residues are allelopathic, the study will again be inadvertently biased against the low-disturbance (and shallow placement) treatments.

Side-band and seed-furrow fertilizers are sometimes found to be more important in no-till than tilled systems. Again, this isn't unusual or unexpected. Early planted no-till crops often find the soil environment a bit wetter and colder and their early growth responds favorably to use of side-band and pop-up fertilizers, and the enhanced early growth occasionally improves grain yield, especially in areas where pollination or grain fill is adversely affected by delays in crop maturity. In such studies, be careful to determine if there was a treatment where N and/or P and/or K in the side-band and/or pop-up were used in all tillage systems. (Producers and researchers often overlook the good combinations: pop-up *plus* side-band, not just one or the other.) Carefully look at the treatment methods and treatment rates. Broadcast N is not as efficient as banded N. Surface applications are often not as efficient as shallow placement. Has the no-till treatment been in place for a number of years prior to the start of the study, or is the soil structure and biology still in transition?

Deep P (and K) may be needed for higher yield in a few soils or fields, but the evidence is extremely weak (despite intense study) and the measured yield effects are typically quite small to nonexistent. Having appreciable P and other nutrients at depth has intuitive appeal, and may yet prove important in arid environments. But, looking at long-term no-till systems with earthworms, the fauna are often moving nutrients *and organic matter* deeper than mechanical placement does, and the biology does that in all areas, not just the shank area. Nutrients are going to depth as linings in the faunal burrows. Roots follow these channels, which are also the pathway for water and oxygen to enter the soil. The crop benefits when roots, water, and available nutrients are in close proximity. With deep mechanical placement *the nutrients will get cycled back to the surface by the plants* and the mechanical placement will need to be repeated. Earthworms and other soil organisms, however, continue moving nutrients effectively year after year, as well as making some nutrients more available to crops.

In long-term no-till systems with earthworms, the fauna are moving nutrients and organic matter deeper than mechanical placement does, and the biology does that in all areas, not just the shank area. Earthworms and other soil organisms continue moving nutrients year after year, while mechanical placement must be repeated.

The fertilizer placement studies discussed here are typical of other unpublished experiments across the U.S. and Canada. Agronomic soil and crop sciences are often broken into pieces that are easier to study, but the pieces are not necessarily easily fitted back together into a system by producers or by the investigators (including the authors of this article). Many crop nutrition researchers do not understand no-till sufficiently, and so they design experiments that are supposed to define this mysterious tillage by fertility interaction instead of just focusing on nutrient cycling and distribution characteristics under continuous no-till, and what needs to be done to efficiently fertilize no-till crops.

Conclusion

Stratification is best thought of as *normal* nutrient distribution. Deep placement of fertilizers or manure (while disturbing as little of the soil volume and surface mulch as possible) may have some applicability as a *one-time* corrective measure on a soil with exceptionally low nutrient status at depth, but which is otherwise productive. However, the best long-term approach will be to ensure an adequate (or slight surplus) crop nutritional status using shallow (e.g., 2-inch depth) subsurface placement or surface applications, and allowing natural processes to gradually redistribute those nutrients to depth. Improving other aspects of no-till agronomy will likely have a better economic return for producers than repeatedly attempting to mechanically place nutrients at depth, especially when the deep-placement operations disrupt the network of biopores and aggregation that form slowly under many years of continuous no-till.