

# Aggregation of a Silty Clay Loam Soil by Mycorrhizal Onion Roots<sup>1</sup>

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## ABSTRACT

Onion plants (*Allium cepa* L.) inoculated in the root zone with a vesicular-arbuscular mycorrhizal (VAM) fungus, or left uninoculated, were grown in potted soil for 230 d to determine the influence of the VAM fungus (*Glomus macrocarpum* Tul. and Tul.) on soil structure. The silty clay loam soil was maintained at a moisture content between 25 and 30%. Paired inoculated (+M) and uninoculated (-M) plants were harvested (20 pairs over 150 d) beginning 80 d after planting. Relationships between plant, fungal, and soil parameters and changes with time were evaluated by regression analysis. Root colonization by the VAM fungus in +M plants ranged from 49% to 60% over the sampling period, while no mycorrhizae were detected in the -M plants. Total dry mass of VAM plants was five to six times that of the non-VAM plants. Soil from the +M treatment was significantly better aggregated, more porous, and had greater water permeability than -M soil. Root dry mass and VAM hyphal density in the +M soil were both significantly correlated with the relative abundance of water-stable soil macroaggregates. Correlation of root mass with aggregate abundance was stronger, however, suggesting that soil changes were mainly mediated by direct root effects of a host plant whose growth was stimulated dramatically by its VAM fungal endophyte.

**Additional Index Words:** *Allium cepa*, *Glomus macrocarpum*, soil porosity, soil permeability, symbiosis.

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VESICULAR-ARBUSCULAR MYCORRHIZAL (VAM) fungi colonize the roots of most crop and forage plants. Their hyphae function as extensions of the host plant's root system and reach microsites outside the rhizosphere which are not accessible to the root. A voluminous literature has clarified the beneficial and often essential role of VAM fungi in supplying nutrients to the host plant (10, 18, 24, 27). In contrast, only a few studies have considered VAM-fungal influence on the biotic (2) and particularly the abiotic (31) components of the soil. Nicolson (19, 20), Koske et al. (14), Sutton and Sheppard (28), and Clough and Sutton (6) showed by field observations and controlled pot experiments that VAM fungi, in association with grasses and herbs, were instrumental in aggregating sand-dune soil. Forster (7), Forster and Nicolson (8, 9), and Jehne and Thompson (11) confirmed the importance of VAM hyphae in aggregating sand when higher plants were present. Tisdall and Oades (29) found that VAM fungi colonizing ryegrass (*Lolium perenne*) roots were the principal factor in aggregating a degraded loamy soil. Reid and Goss (25), also working with loamy soil, found direct effects of living roots on soil structure but failed to confirm a correlation

between root colonization by VAM fungi and aggregate stability. Recently, Rothwell (26) and Fugill Sencindiver (reported by Rothwell) concluded VAM-fungal hyphae were important in stabilizing revegetated sandy-loam mine soil. Many of the workers cited above did not include non-VAM plants in their experiments or field observations to unequivocally the role of the fungus in soil aggregation.

The purpose of our experiment was to determine the effect of a VAM fungus on the structure of a loam soil, utilizing non-VAM plants for comparison. Changes with time in the plant-soil system. We used onion (*Allium cepa* L.), a coarse-rooted host plant highly dependent (15, 22, 23) on its fungal endophyte for its growth, in order to maximize fungal effect.

## MATERIALS AND METHODS

### Experimental Design and Evaluations

Plants treated with a VAM fungus (+M) or not treated (-M), were maintained in a random design and grown 80 d until +M plants were discernibly larger than -M plants. Pairs of +M and -M plants were then selected at random (20 pairs over a 150-d sampling period), harvested at intervals and evaluated for pertinent plant, fungal, and soil parameters as outlined below. Relationships between these parameters and the change of parameters with time were evaluated by regression analysis. Predicted values (statistical best estimates, analogous to mean values) of parameters calculated from optimum regression functions, accurately fitted to the populations of data points.

### Soil and Biological Materials

A calcareous silty-clay loam (Typic Xerorthent, 12% silt, 68% silt, 20% clay) soil of the Balcom Series from Kern County, California, of pH 8 and limiting in available phosphorus and organic matter, was used (5). The soil was sieved (2 mm), air-dried, autoclaved, and amended with hydroxyapatite (75 mg/kg) as a P source. Autoclaving insured the absence of viable VAM fungi and also produced a desirable decrease in aggregate stability of the native soil. Onion plants were inoculated with the VAM fungus *Glomus macrocarpum* Tul. and Tul. or left uninoculated. The fungus had been isolated from the native Balcom soil and cultured on strawberry (*Fragaria vesca* L. Duchesne). All soils were inoculated with a VAM propagule-free microbial suspension prepared from unsterilized Balcom soil (1:3 slurry of soil in distilled water, sieved three times through 45- $\mu$ m screen).

### Growth Conditions

Plants were grown in a greenhouse in Albany, CA, from November through January. Automatic temperature control systems were operational above and below 25 and 18°C, respectively. Daylight was extended to 16 h November through January, by providing supplementary lighting (500  $\mu$ mol  $m^{-2}s^{-1}$ ). Surface-sterilized seeds were germinated in sand and the 1-week seedlings transplanted one each to 1 L pots filled with soil over a bottom layer (40 mm) of gravel. Surface-sterilized spores of *G. macrocarpum* were added, 100 per plant, to the roots at transplanting. Soil moisture, determined by pot weight, was maintained at 2.300 g/kg by watering with deionized water from below.

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Table 1. Host-plant and fungal parameters in +M or -M soils correlated with time over a sampling period 80 to 230 d after planting.

Parameter	Treatment	f(x)†	Regression analysis			
			Predicted value		r <sup>2</sup>	P
			80 d	230 d		
VAM colonization (% root length)	+M		49.00	66.00	0.17	<0.10
Total plant dry mass (g)‡	+M		0.97	17.89	0.93	<0.01
	-M	E	0.16	3.51	0.70	<0.01
Root dry mass (g)	+M		0.07	7.64	0.90	<0.01
	-M		0.04	1.04	0.71	<0.01
Shoot dry mass (g)	+M		1.27	10.26	0.87	<0.01
	-M	E	0.10	1.99	0.69	<0.01
Root/shoot mass ratio	+M	E	0.25	0.99	0.68	<0.01
	-M		0.59	0.76	0.15	<0.10
VAM-colonized root mass (g)	+M		0.02	2.09	0.85	<0.01
VAM hyphal density (mg soil)	+M		13.1	24.2	0.38	<0.01
VAM (dead) hyphal density (mg/g soil)	-M		9.4	12.2	0.09	>0.10
Non-VAM hyphal density (mg/g soil)	+M	Q	30.6	42.9§	0.37	<0.05
	-M		30.2	29.3	0.01	>0.10

† Best-fit regression functions were linear, except as indicated: E — exponential; Q — quadratic.

‡ See Fig. 1.

§ Maximum value at 149 d.

complete nutrient solution except for P (5) was administered twice per 7 d.

### Assays

The soil was allowed to dry to a moisture content of approximately 190 g/kg (below the plastic limit, 210 g/kg) prior to harvest. The soil mass above the gravel bed was removed intact from the pot and an undisturbed cylindrical core was taken. The remaining damp soil was then crumbled by hand (crumbs <10 mm diam) while completely removing the onion roots. Care was taken to perform the crumbling operation as reproducibly as possible. Samples of thoroughly mixed soil were taken for determination of moisture content, water-stable aggregates, and hyphal density.

In hyphal density (total length of hyphae per unit dry soil mass) determinations (1), fungal hyphae larger than 5  $\mu$ m in diameter were adjudged to be predominantly VAM, those <5  $\mu$ m to be predominantly non-VAM (saprophytic) fungal hyphae. The degree of root colonization by the VAM fungus (percent root length colonized) was determined by the line intercept method (16) on stained specimens (21). Shoots and remaining roots were dried (24 h, 70°C) and weighed. Total root mass included roots recovered from the soil core and the gravel bed. An estimate of VAM-colonized root mass was obtained by multiplying total root mass by percent root length colonized.

The size distribution (relative abundance by size class) of water-stable aggregates was determined by wet sieving according to Yoder (33) with several modifications. A 100 g (dry mass) sample of soil with approximately 190 g/kg moisture content was distributed uniformly on the top sieve of a stack of sieves (203 mm diam, screen openings 2.00, 1.00, 0.500, 0.250, and 0.125 mm), which was mechanically raised and lowered for 30 min at 20 cycles/minute with a stroke of 19 mm, in a water bath (deionized water at 25°C). The soil remained immersed in water at the top of the stroke. The sieves were drained, dried, net contents weighed *in situ*, and weights calculated as percent of soil mass originally added to the top sieve. The mass percent of soil passing through the bottom sieve was determined by difference.

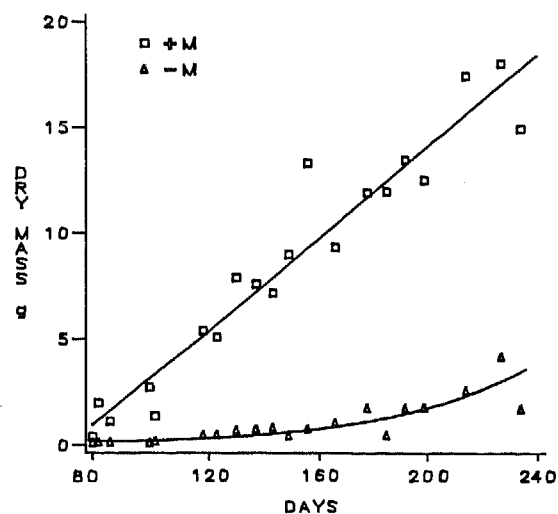


Fig. 1. Total dry mass of +M and -M onion plants harvested at intervals over a sampling period 80 to 230 d after planting. Optimum regression functions (linear for +M, exponential for -M) were fitted to the data. For statistical parameters, see Table 1.

Physical parameters of the undisturbed soil were determined using the cylindrical soil cores (30 mm by 54 mm diam). Total porosity was calculated from bulk density using assumed particle density of 2.65 g/cm<sup>3</sup> (32). Pore size distribution (percent of total pore volume attributed to pores of specified diameter) was determined by drainage of water-saturated cores at suctions of 0.49 and 3.92 kPa (5 and 40 cm water) using the hanging-water-column method (32). The selected suctions correspond in the capillary model to pore diameters >600  $\mu$ m and >75  $\mu$ m, respectively. Pore volume percentages for pores in the diameter range 75 to 600  $\mu$ m and <75  $\mu$ m were calculated by difference. Permeability (saturated hydraulic conductivity) was determined by the falling-head method (13) using a relatively low hydraulic gradient (between 2 and 1).

Two pots of autoclaved, uninoculated, unplanted soil (control soil) were watered as above for 7 d (time required to wet to 300 g/kg and then dry to 190 g/kg moisture content) and then harvested for determination of baseline values of soil and fungal parameters.

## RESULTS

### Plant and Fungal Parameters

The roots of +M plants were 49% percent colonized by VAM fungus at the start of the sampling period, as shown by predicted values, and colonization gradually increased thereafter to 66% (Table 1). The -M roots were not colonized. Total plant dry mass (Table 1, Fig. 1) and root and shoot dry masses of +M and -M plants (Table 1) increased at markedly different rates during the sampling period. While total mass of both +M and -M plants increased approximately 20-fold, the +M/-M mass ratio remained nearly constant with a value of 5 to 6. In agreement with earlier findings (3), the root/shoot ratio in +M plants was smaller than in -M plants throughout most of the sampling period. An accelerating rise of the ratio with time in +M plants, however, brought the +M value above that of the -M value at the end. The +M root dry mass was more than seven times that of -M plants at the end of the sampling period (Table 1).

**Table 2. Significant correlations between host-plant, host-fungal or fungal parameters in +M soils sampled over a period 80 to 230 d after planting.**

Host	Correlated parameters†		Regression analysis‡	
	Host-fungal (Intraradical)	Fungal (Extraradical)	r <sup>2</sup>	P
Total dry mass (g)	←————→	VAM hyphal density (m/g soil)	0.397	<0.01
	Colonized root mass (g) ←————→	VAM hyphal density (m/g soil)	0.233	<0.05
Root/shoot ratio	←————→	←————→	0.170	<0.10
Root/shoot ratio	←————→	VAM hyphal density (m/g soil)	0.342	<0.01

† Correlation is between pairs of parameters connected by double arrow.

‡ Best-fit regression functions all linear; slopes of regression lines all positive.

**Table 3. Size distribution (relative abundance) of water-stable aggregates wet-sieved from +M and -M soils, correlated with time over a sampling period 80 to 230 d after planting.**

Aggregate size (mm)	Relative abundance (%)†		Significance (P)	
	80 d	230 d	r <sup>2</sup>	Slope difference‡
<b>+M</b>				
>2.00¶	19.0 (20.5)§	31.9	<0.01	<0.01
1.00 to 2.00	16.8 (18.1)	14.0	<0.05	>0.10
0.50 to 1.00	12.4 (13.6)	10.0	<0.05	>0.10
0.25 to 0.50	9.4 (9.7)	6.8	<0.01	<0.05
0.125 to 0.25	7.6 (7.1)	5.8	<0.10	>0.10
<0.125	34.8 (31.0)	31.6	>0.10	<0.05
<b>-M</b>				
>2.00¶	19.6	18.6	>0.10	
1.00 to 2.00	17.7	15.8	>0.10	
0.50 to 1.00	13.0	12.1	>0.10	
0.25 to 0.50	9.1	8.8	>0.10	
0.125 to 0.25	6.9	5.8	>0.10	
<0.125	33.7	38.3	<0.10	

† Initial (80 d) and final (230 d) predicted values obtained by linear (best-fit) regression analysis of relative amount (% total soil) of soil fraction vs. time of harvest.

‡ Difference in slope of regression lines obtained from +M and -M soils.

§ Values in parentheses represent mean relative abundance of soil fraction obtained from sterilized, unplanted uninoculated control soil, after 7-d incubation. These control values are applicable to both +M and -M soils.

¶ See Fig. 2.

Predicted values for VAM and non-VAM hyphal densities in both +M and -M soils at start of sampling at 80 d (Table 1) were similar to mean values found in sterilized, uninoculated control soil incubated for 7 d (10.8 m/g for VAM hyphae, 30.2 m/g for non-VAM hyphae). This constancy from 7 to 80 d for VAM hyphae probably resulted from the dead mycelium present after sterilization, with only a little growth balanced by slight decay (30). In the case of non-VAM, saprophytic hyphae, a living population which re-established itself during the first 7 d evidently reached dynamic equilibrium already within that short time. In -M soil, both VAM and non-VAM hyphal densities remained at the 7-d level throughout the sampling period, as shown by predicted values (Table 1). In +M soil, on the other hand, VAM hyphae almost doubled in density during the sampling period, while non-VAM hyphae increased to a maximum abundance at 149 d, then decreased again to near the initial value at the end, 230 d. The temporary increase in non-VAM hyphae evidently represented a transient shift in the dynamic equilibrium of the population probably resulting from the increased plant organic input to the +M soil.

The density of VAM hyphae in the +M soil and

the mass of colonized roots sampled during the period were significantly correlated (Table 2), while the relationship with percent colonization of root length was not significant. Reflecting the better nutrition of those +M plants which had the most extensive VAM hyphal systems, there was also a significant correlation in +M plants between total plant dry mass and VAM hyphal density in the soil (Table 2). A lack of significant correlation between percent colonization of root length and plant dry mass may indicate there were differences in the need for nutrient-uptake (extraradical) and nutrient-transfer (intraradical) organs in the course of the association's development (4). In +M plants the root/shoot ratio was significantly related to both percent VAM colonization of roots and to density of VAM hyphae in the soil (Table 2). The density of non-VAM hyphae was not significantly related to any plant parameters in either +M or -M soils. Similarly, the density of VAM hyphae in -M soil (background level of dead hyphae, Table 1) yielded no significant correlations.

#### Soil-mycorrhiza Relations: Water-stable Aggregates

The size distributions (relative abundances) of water-stable aggregates in +M and -M soils (predicted values) and in the 7-d incubated control soils (mean value) were similar at the start of the sampling period (Table 3), indicating little change in soil structure during the initial 80-d growth period. During the subsequent sampling period the -M soil disaggregated slightly, as seen by a small but significant increase in the relative abundance of the smallest (<0.125 mm) soil particles at the expense of the larger particles. The +M soil, in contrast, showed a significant, large (68%) increase in relative abundance of macroaggregates (>2.00 mm) at the expense of smaller particles in the size range 0.125 to 2.00 mm. Evidently the smaller grains and aggregates were increasingly bound together into macroaggregates (31). The different development of the two soils over the course of the sampling period was confirmed by the significant difference in regression line slopes of the +M and -M soils for three of the six particle fractions (Table 3).

Moisture content of the soil samples immersed for wet sieving (adjusted by pot weight at harvest to approximately 19% moisture) fell within a range which, for soils wet-sieved by Kemper and Rosenau (12), gave greatest discrimination between soils, but also greatest sensitivity to variations in moisture content within a given soil. We tested (regression analysis) the effect on our wet-sieving results of slight experimental errors in adjusting the moisture content of the soil samples. Our results did depend on variations in moisture content,

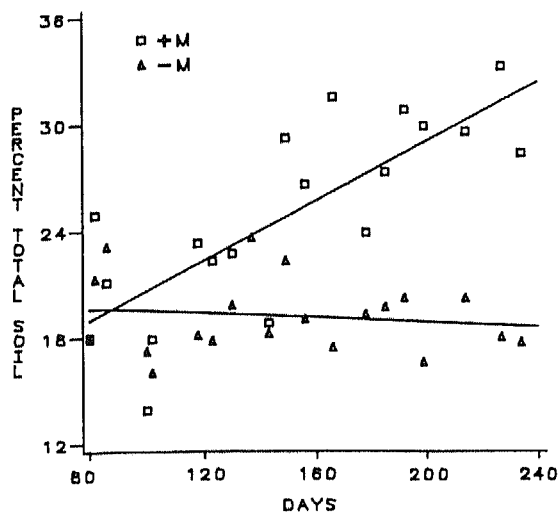


Fig. 2. Percent of total soil mass found in macroaggregate (>2.00 mm diam) fractions wet-sieved from +M and -M soils harvested at intervals over a sampling period 80 to 230 d after planting. This typical plot illustrates scatter of the data and fit of the optimum (linear) regression functions. For statistical parameters of this and other plots (not shown), see Table 3.

but these variations for both +M and -M samples taken throughout the experiment showed no significant correlation either with treatment or with time. Experimental error in adjusting moisture at harvest thus contributed to the overall scatter of our aggregate abundance values as a function of time (Fig. 2), but did not alter the relative levels and trends of aggregation in +M, or disaggregation in -M soils.

Regression analyses of the abundances of water-stable soil aggregates of three sizes (>2.00, 0.250-0.500, and <0.125 mm) against root mass or the density of VAM or non-VAM fungal hyphae in the soil showed a different pattern of significant correlations in +M and -M soils (five significant correlations from the total of 18 regressions: Table 4). In +M soils, aggregation was positively correlated with root mass and also with density of VAM hyphae. The correlation with root mass was the stronger, suggesting that root effects were primarily responsible for promoting aggregation. In -M soils, no significant correlation was found with root mass; evidently the quantity of roots (Table 1) was too slight to exert a statistically significant effect. A negative correlation was found between aggregation and the density of dead VAM hyphae (Table 4). This suggests that dead hyphal material in the -M soil was consumed by other microorganisms that promoted aggregation. Non-VAM hyphal density showed no significant correlation with aggregation in either +M or -M soils.

#### Soil-mycorrhiza Relations: Properties of Intact Soil

The total porosities (Table 5) of both +M and -M soils sampled by coring at the start of the sampling period were somewhat less than that of the 7-d control soil ( $48.2 \pm 0.1$ ), reflecting the effects of watering during the initial 80-d growth period. During the course of the sampling period, total porosity of +M soil showed no statistical change, while that of -M soil decreased significantly. Difference in slopes of the regression lines was significant ( $P < 0.05$ ). Paralleling

Table 4. Significant correlations of water-stable soil aggregates with either root mass or hyphal density.†

Treatment	Biological variable	Aggregate‡ size (mm)	Regression analysis§		
			Slope	r <sup>2</sup>	P
+M	Root mass (g)	>2.00	+	0.54	<0.01
+M	Root mass (g)	0.25 to 0.50	-	0.51	<0.01
+M	VAM hyphae (m/g soil)	>2.00	+	0.20	<0.10
-M	VAM (dead) hyphae (m/g soil)	>2.00	-	0.18	<0.10
-M	VAM (dead) hyphae (m/g soil)	<0.125	+	0.22	<0.05

† Regression analyses included both +M and -M samples taken over the period 80 to 230 d after planting, and both VAM and non-VAM hyphal densities. Soil aggregates were arbitrarily limited to three size-classes: >2.00, 0.250 to 0.500, and <0.125 mm.

‡ Regressed soil variable is the relative abundance (% of total soil) of aggregates in specified size range. Note that increased soil aggregation implies increased relative abundance of macroaggregates, >2.00 m diam, but decreased relative abundance of smaller aggregates or particles.

§ Best-fit regression functions all linear.

Table 5. Parameters of intact +M and -M soils core-sampled over a period 80 to 230 d after planting, correlated with time.

Treatment	Parameter	Regression analysis†			
		Predicted value		r <sup>2</sup>	P
		80 d	230 d		
+M	Root density (mg/g soil)	0.17	0.59	0.29	<0.05
-M	Root density (mg/g soil)	0.01	0.16	0.55	<0.01
+M	Total porosity (% bulk volume)	45.1	44.9	0.01	>0.10
-M	Total porosity (% bulk volume)	47.4	43.5	0.32	<0.05
+M	Permeability (log mm sec <sup>-1</sup> × 10 <sup>7</sup> )	1.7	1.8	0.01	>0.10
-M	Permeability (log mm sec <sup>-1</sup> × 10 <sup>7</sup> )	2.0	1.4	0.17	<0.10

† Best-fit regression functions all linear.

Table 6. Correlation of pore-size distribution (percent of total pore volume) with total porosity in +M and -M soils core-sampled over a period 80 to 230 d after planting.

Pore diameter (μm)	Regression analysis†			
	% total pore volume (predicted value)		r <sup>2</sup>	P
	At maximum total porosity	At minimum total porosity		
	+M			
>600	3.0	2.3	0.03	>0.10
75 to 600	9.2	6.9	0.15	>0.10
<75	87.8	90.8	0.15	>0.10
	-M			
>600	2.8	2.0	0.04	>0.10
75 to 600	14.4	4.9	0.46	<0.01
<75	82.8	93.1	0.43	<0.01

† Best-fit regression functions all linear.

the changes in total porosity, water permeability decreased significantly in -M soil but remained statistically constant in +M soil (Table 5). Again, regression line slopes were significantly different ( $P < 0.10$ ). No significant change in pore-size distribution with time was found in either -M or +M soils. However, the pore-size distribution was significantly correlated with changes in total porosity in -M soils (Table 6). Associated with lesser total porosity was a 200% decrease in the relative amount of pores in the size range 75 to 600 μm, compensated by a 10% increase in the large amount of smallest (<75 μm) pores. The relative amount of pores >600 μm in diameter remained unchanged. Paralleling the constant porosity in +M soil

(Table 5), no significant correlations with this parameter (Table 6) were found in +M soil.

Root densities in the soil cores were appreciably greater in +M than in -M soils (Table 5). The greater density of roots (and associated fungal mycelia) in the soils of +M plants apparently counteracted the effects of slaking induced by periodic variations in soil moisture during watering. As a result, +M soil was more porous and permeable at the end of the test period than -M soil.

## DISCUSSION

The results of this experiment showed that growth of VAM-colonized onion roots in a fine-textured loam increased the relative abundance of water-stable soil macroaggregates, and prevented bulk consolidation, while disaggregation and consolidation occurred in the soil of non-VAM plants. These results extend insights gained from previous studies (25,29,30) which demonstrated in controlled pot experiments an appreciable aggregation of loamy soils by VAM roots of white clover (*Trifolium repens*), ryegrass, lucerne (*Medicago sativa*), and maize (*Zea mays*). Tisdall and Oades (29, 30) ascribed the increase in macroaggregates associated with the large fibrous root system of ryegrass primarily to the binding together of smaller grains and aggregates (31) by VAM hyphae. Reid and Goss (25), whose plants were only sparsely colonized by VAM fungi, concluded that action of the fungus on the soil was unimportant and that aggregation was largely the result of organic exudates released directly by the living roots. These divergent results and interpretation were apparently influenced at least partly by differences in techniques. Tisdall and Oades (29) assessed aggregate stability by wet sieving of air-dried soil containing roots, while Reid and Goss (25) relied primarily on a turbidimetric method applied to moist soil samples. Since neither investigation included control plants completely free of VAM-fungal colonization, the effects of VAM fungi on the soil, either directly or mediated by the VAM root system, could not be definitively evaluated. In our investigation, aggregate stability was tested by wet-sieving of moist soil. This technique thus had some elements in common with those of both previous investigations (25, 29). Like Reid and Goss, we removed newly formed roots completely from soil samples before testing for aggregation. Differing from both previous studies, our investigation included a comparison set of non-VAM plants whose action on the soil could be compared with the VAM-colonized set, to assess relative contributions to aggregation by roots or VAM hyphae.

The extent to which the VAM fungus alone facilitates the formation of stable aggregates cannot be inferred from our results. The greater hyphal density in the better aggregated soil of VAM plants (Tables 1, 3) is consistent with fungal contributions to aggregate stability. Our data (Table 4) suggest, however, that with the coarse roots of VAM onion used in this experiment, fungal effects on the soil were mainly mediated by a host plant whose growth was dramatically stimulated by its VAM-fungal endophyte. Differences in host-endophyte combinations and edaphic, cli-

matic, and cultural conditions are known to affect the development of both symbiotic partners and their effects on one another (17). It may be expected that these conditions will also affect the impact of the symbiosis on its growth medium. The assessment of this impact, especially under field conditions, is in its infancy, but promises to play an important role in soil conservation efforts.

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## DIVISION S-4—SOIL FERTILITY AND PLANT NUTRITION

### Recovery of Fertilizer Nitrogen by Wheat as Affected by Fallow Method<sup>1</sup>

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#### ABSTRACT

The fate of fertilizer N applied to crops is of both environmental and economic concern. To follow fertilizer N recovery in western Nebraska, depleted-<sup>15</sup>N NH<sub>4</sub>NO<sub>3</sub> was surface broadcast in April on winter wheat (*Triticum aestivum* L.) growing on plots fallowed the previous year by plowing, sub tillage, and no-till. Quantities of labeled N taken up by the growing crop, in the upper 100 mm of soil as inorganic N, and in both visible and partially decomposed crop residues, were followed on two sets of plots through the crop-fallow-crop sequence (approximately 117 weeks). About 16 to 18% of the labeled N was removed in the grain of the first wheat crop, with an additional 3 to 5% in the second crop. Labeled inorganic soil N decreased to <5% within 1 yr, with little effect of fallow method. No more than 4% was in visible residues at any time for all except no-till fallow, for which 7 to 13% of the labeled N was found in visible residues from heading of the first crop through the entire fallow period until the second crop was seeded. Likewise, 4 to 9% of the labeled N applied was found in partially decomposed residues of no-till during this period, compared to no more than 2% for the plow and sub till treatments. Total N in both residue pools combined decreased 50% from October to April of the fallow year for N-fertilized wheat and 25% for unfertilized wheat. Most of the labeled N in the straw found in the visible residue pool by October was transferred over winter to either the partially decomposed pool or to other undetermined pools (including soil organic matter, microbial biomass, and losses to the atmosphere). Results show that, compared to plow and sub till, no-till fallow enhanced retention of labeled N in the several crop residue pools and increased N uptake by the two wheat crops.

*Additional Index Words:* *Triticum aestivum* L., no-till, residue management, N cycling, N-use efficiency.

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THE EFFECTS OF FALLOW METHOD on various crop production parameters have been extensively studied for winter wheat (*Triticum aestivum* L.)-fallow rotations in semiarid regions (Black and Power, 1965; Power *et al.*, 1984; Unger and McCalla, 1980; Zingg and Whitfield, 1957). Most studies were initially concerned with effects of tillage method on water conservation because water availability usually limits production in semiarid regions (Duley and Russel, 1939). Earlier research has shown that maintaining crop residues on the soil surface during the fallow period usually increased the amount of available water stored in the soil (Fenster and Peterson, 1979; Smika and Wicks, 1968). No-till methods of fallow (ecofallow) often maximize water conservation and thus produce greatest potential for grain production.

A review of published data on wheat yields obtained after fallowing by various methods revealed that the extra water conserved by leaving crop residues on the soil surface often failed to increase yields (Fenster and Peterson, 1979; Power *et al.*, 1984; Unger and McCalla, 1980). Also, in many studies, protein content of grain was lowered with reduced and no-tillage methods (Power *et al.*, 1984; Unger and McCalla, 1980; Zingg and Whitfield, 1957). These observations have suggested that leaving crop residues on the soil surface in some manner limits availability and uptake of N by wheat.

With these observations and 9 yr of previous data from an ongoing tillage experiment at Sidney, NE (Fenster and Peterson, 1979), comprehensive research was initiated near Sidney to study the soil environment, microbial populations, and N transformations resulting from microbial activity as affected by tillage practices (Broder *et al.*, 1984; Linn and Doran, 1984; Mielke *et al.*, 1984; Wilhelm *et al.*, 1982). The experiment reported here was conducted with isotopic techniques to determine the effects of fallow method on the cycling and uptake of fertilizer N by winter wheat.