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Organic matter addition, N, and residue burning effects on infiltration, biological, and physical properties of an intensively tilled silt-loam soil☆

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Abstract

Seventy years of different management treatments have produced significant differences in runoff, erosion, and ponded infiltration rate in a winter wheat (*Triticum aestivum* L.)–summer fallow experiment in OR, USA. We tested the hypothesis that differences in infiltration are due to changes in soil structure related to treatment-induced biological changes. All plots received the same tillage (plow and summer rod-weeding). Manure (containing 111 kg N ha^{-1}), pea (*Pisum sativum* L.), vine (containing 34 kg N ha^{-1}), or N additions of 0, 45 and 90 kg ha^{-1} were treatment variables with burning of residue as an additional factor within N-treatments. We measured soil organic C and N, water stability of whole soil, water stable aggregates, percolation through soil columns, glomalin, soil-aggregating basidiomycetes, earthworm populations, and dry sieve aggregate fractions. Infiltration was correlated ($r = 0.67$–0.95) to C, N, stability of whole soil, percolation, and glomalin. Basidiomycete extracellular carbohydrate assay values and earthworm populations did not follow soil C concentration, but appeared to be more sensitive to residue burning and to the addition of pea vine residue and manure. Dry sieve fractions were not well correlated to the other variables. Burning reduced ($p < 0.05$) water stability of whole soil, total glomalin, basidiomycetes, and earthworm counts. It also reduced dry aggregates of 0.5–2.0 mm size, but neither burning nor N fertilizer affected total C or total N or ponded infiltration rate. Water stability of whole soil and of 1–2-mm aggregates was greater at 45 kg N ha^{-1} than in the 0 and 90 kg N ha^{-1} treatments. Zero N fertilizer produced significantly greater 0.5–2.0 mm dry aggregate fractions. We conclude that differences in infiltration measured in the field are related to relatively small differences in aggregate stability, but not closely related to N or residue burning treatments. The lack of an effect of N fertilizer or residue burning on total C and N, along with the excellent correlation between glomalin and total C

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($r = 0.99$) and total N ($r = 0.98$), indicates that the major pool of soil carbon may be dependent on arbuscular mycorrhizal fungi.

Keywords: Infiltration; Aggregate stability; Glomalin; Basidiomycetes; Earthworms; Soil organic matter

1. Introduction

Water infiltration into soil is an important aspect of both natural and manipulated landscapes. While simple in concept, it is difficult to identify or directly measure the relative importance of several pathways water can take as it penetrates the soil surface. Soil aggregation, porosity, surface connected pores produced by roots and fauna, and the stratification of organic matter can all play a role. Our ability to make useful recommendations on the effects of different types of tillage, minimum disturbance seeding, addition or subtraction of surface residues, soil inversion, and other soil manipulations depends on improving our understanding of the exact mechanisms by which water infiltrates under different circumstances. For example, tillage can cause rapid, significant physical changes, which can also be detrimental to the functioning of soil biota such as arbuscular mycorrhizal fungi (Wright et al., 1999).

Pikul and Allmaras (1986) measured saturated conductivity in the same plots used in this study, and concluded that the tillage pan was the most restrictive layer and that the treatment where manure is applied was the only one with significantly greater saturated conductivity. They used a double-tube method at the depth of the plow pan, but steady-state ponded infiltration should be limited by the same restrictive layer if the cylinders used to contain flow are driven to or below the same depth.

Different organic C levels can be the result of different intensities of tillage (Elliott, 1986). In studies where all plots receive the same tillage, treatment comparisons are not confounded by stratification versus mixed surface horizon, or development of long-term macropores. However, differences in soil properties may be a result of decades of differential residue inputs. Soil organic C levels can be related to N and manure inputs (Monreal et al., 1997), and aggregate stability is generally correlated with organic C (Pierson and Mulla, 1990; Smettem et al., 1992).

Prior research in the same plots used for the research reported here concluded that, while there were no soil aggregate mean weight diameter differences, total soil organic C was related to porosity (measured by mercury intrusion) and infiltration (Pikul and Zuzel, 1994). Total organic C measures a variety of substances (sugars, proteins, aromatic hydrocarbons, etc.), which are likely to have variable effects on aggregate properties. A more specific assay like glomalin quantification may produce better correlation with aggregate stability and may vary with treatments due to arbuscular mycorrhizal fungal responses to protection by organic matter sources (Franzluebbers et al., 2000). Likewise, basidiomycete fungi populations, which are associated with wheat lignin, could differ between treatments and stabilize aggregates because of the soil aggregating mucilage they produce (Caesar-TonThat, 2002).

Our objective was to test the hypothesis that differences in infiltration in an intensively tilled long-term study can be related to the effect of treatments on biological and structural soil differences.

2. Materials and methods

A winter wheat–summer fallow experiment was established in 1931. All treatments received the same intensive tillage, which was inversion with a plow in the spring followed by cultivation and shallow weeding to maintain traditional black fallow during alternate summers. Treatment effects are not easily visible in clod size or soil color on the dry, residue-free surface during the summer fallow period or after planting. When the soil is close to saturation, however, some of the treatments can be distinguished by subtle color and light reflection differences. Water runoff from five of the treatments was monitored from 1998 to 2000, and found to be remarkably different and correlated to soil organic C levels associated with residue and N management (Williams, 2004).

The experimental plots are located near Pendleton, OR (45°43′N, 118°38′W, elevation 458 m). Annual precipitation averages 420 mm and falls mostly as rain during the winter. Temperatures average −0.6 °C in January. Summers are hot and dry, with an average temperature of 21 °C in July. The soil is Walla Walla silt-loam (coarse–silty, mixed, superactive, mesic Typic Haploxeroll containing about 18% clay, 70% silt and 12% fine to very fine sand).

Tillage used in the experiment is common in the region, and consists of moldboard plowing in the spring to 20 cm, followed by smoothing with a field cultivator and tine harrow. Shallow tillage with a rod-weeder is used three or four times during the summer to control weeds and maintain a dust mulch that preserves seed-zone moisture through the summer-fallow period. Winter wheat is planted the following October. The rotation is therefore a two-year cycle of 14 months of fallow followed by 10 months of winter wheat with harvest in July of every other year. The risk of water runoff and erosion is greatest in the winter following planting, when residue cover is minimal and the soil surface has been finely pulverized by spring and summer tillage.

Details of the history of the experiment, C and N balances, yields, and other factors can be found in Rasmussen and Parton (1994). Five of the nine residue management and N treatments (Table 1) have not changed over the 70-year history of the experiment. Those treatments are 22.4 Mg ha^{-1} fresh manure or 2.24 Mg ha^{-1} pea vines added in the spring before plowing, stubble burned in the fall after wheat harvest, stubble burned in the spring before plowing, and the unburned, zero-N check. The unburned, 90 kg N ha^{-1} treatment was only 34 kg N ha^{-1} until 34 years ago. The other three treatments have been in place for at least 22 years. The manure and pea vine treatments contribute about 111 and 34 kg N ha^{-1} per crop cycle, respectively.

The plots are 12 m × 40 m and arranged in four complete blocks. Two of the blocks are in the winter wheat crop cycle during odd-numbered years while the other two are in fallow, and vice versa for even years. The experiment was established without randomizing the treatments within each block, but extensive investigation of plot-by-plot soil samples and yield data before the experiment started, and subsequently, reveals no biases (Rasmussen and Parton, 1994).

Water runoff measurements were made in the winters of 1998–2000 as reported by Williams (2004). Briefly, lister furrows (small ditches made by a single moldboard plow) separated the 12 m×40 m plots to prevent overland flow from one treatment to the next. Weirs and stage recorders at the furrow outfall measured runoff. A weather station at the site recorded soil and air temperature, wind speed, and precipitation. Runoff-to-precipitation ratio was calculated for those events where runoff was generated in at least one of the treatments. After log transformation to meet the assumption of normality, runoff-to-precipitation ratio

Table 1
Treatment history of the crop residue experiment established in 1931 near Pendleton, OR, USA

Timing of residue burn	N (kg ha^{-1})	Years in present treatment	Previous treatments	Grain yield relative to not-burned, 90 N treatment	Straw yield relative to not-burned, 90 N treatment
Not burned	Manure (111)	70		1.05	1.06
Not burned	Pea vine (34)	70		0.82	0.93
Not burned	45	34	Not burned: fall disk[a], 34 kg N ha^{-1}, 36 years	0.88	0.94
Not burned	90	34	Not burned: spring disk[a], 34 kg N ha^{-1}, 36 years	1.00	1.00
Spring	90	22	Not burned: spring disk[a], zero N, 36 years; 90 kg N ha^{-1}, 12 years	0.97	1.02
Spring	0	70		0.58	0.71
Spring	45	22	Not burned: fall disk[a], zero N, 36 years; 45 kg N ha^{-1}, 12 years	0.84	0.94
Not burned	0	70		0.60	0.70
Fall	0	70		0.56	0.68

Five treatments have not changed in 70 years. Four treatments were changed in 1967, and two of those were changed again in 1979. Yields are based on a 9-year average. The unburned, 90 kg treatment averaged 4.64 Mg ha^{-1} grain and 7.46 Mg ha^{-1} straw.

[a] Disk was a residue treatment in addition to subsequent spring plow.

was analyzed using ANOVA (SAS Mixed Procedure) type 3 tests of fixed effects ($F \leq 0.05$) and least squares means separation tests (SAS, 1998).

Single-ring infiltration measurements (Bertrand, 1965) were made in all plots in March 2003. The soil was near field capacity due to natural precipitation before measurements were started. Three measurements were made in each plot, each using a different diameter cylinder (20, 30, and 46 cm diameter). The effect of ring diameter on ponded infiltration estimates is the subject of a continuing separate investigation, and for the present study the effect of ring size is ignored in data analysis. Rings were driven into the soil about 25 cm. Rainwater was collected and used to avoid effects of salts (Levy et al., 1994). The water level was maintained at approximately 5 cm above the average soil surface for 30 min before 20 min of infiltration measurement. Data were log transformed before analysis as described below.

Soil samples from all plots were taken from the surface to 15 cm depth in June 2000 (half the plots were in winter wheat crop and half were fallow). Three 2.5 cm cores from three areas of each plot were combined. The samples were air dried and analyzed for total C and N, glomalin, and soil-aggregating basidiomycete populations. This surface soil is free of inorganic carbonates (pH 6.0 in the top 30 cm), so total C analysis measures organic soil C.

2.1. Glomalin analysis

Total (TG), easily extractable (EEG), and the immunoreactive fractions of TG and EEG were determined by methods previously described (Wright and Upadhyaya, 1996, 1998). EEG was extracted with 20 mM citrate, pH 7.0, at 121 °C for 30 min. The supernatant was removed, measured, and a 1 ml aliquot was set aside for assays. TG was extracted from the remaining soil using 50 mM citrate, pH 8.0, at 121 °C in 1-h cycles until the supernatant was straw-colored. Supernatant containing EEG and all sequential extractions for TG were combined. An aliquot was removed for assays. TG and EEG extracts were analyzed for protein by the Bradford protein assay using bovine serum albumin as the standard. The immunoreactive fractions of TG and EEG were quantified by enzyme-linked immunosorbent assay using the monoclonal antibody 32B11.

2.2. Basidiomycete analysis

An enzyme-linked immunosorbent assay was used to detect and quantify soil aggregating basidiomycete fungi (Caesar-TonThat et al., 2001). Soil samples (500 mg/ml) were homogenized in carbonate buffer (20 mM $NaHCO_3$, 28 mM Na_2CO_3, pH 9.6). Homogenates were centrifuged for 10 min (14,000 G) after which 100 μl of the supernatant was loaded in microplate wells (Immulon 4HBX, Dynex Technologies Inc., Chantilly, VA) followed by incubation overnight at 55 °C. After washings with 0.01 M phosphate buffer saline-Tween 20, 0.138 M NaCl, 2.7 mM KCl, pH 7.4 (PBST, Sigma, St. Louis), 100 μl of a 1/10,000 dilution of the third boost rabbit serum was added to each well. Microplates were incubated for 90 min at 22 °C, washed with PBST, and then further incubated for 60 min at 22 °C with a 1/13,000 dilution of horseradish peroxidase-conjugated goat anti-rabbit immunoglobulins (Sigma, St. Louis) added to each well. After PBST washings, the substrate, consisting of a solution of 3,3′,5,5′ tetramethylbenzidine (0.4 g/l) (Pierce, Rockford, IL) and 0.02% hydrogen peroxide, was added. Absorbance was read at 450/655 nm using a BioRad 550 microplate reader (BioRad, Hercules, CA). All samples were processed in triplicate.

2.3. Aggregate size distribution and soil stability

Another surface soil sample (0–15 cm) was taken from 12 locations in each plot using a spade, screened through a 10-mm screen, and air dried. This sample was used for dry sieve measurements (5 min at 1.5 mm vertical vibration), water stability tests, and a percolation test. The water stability tests (Kemper and Rosenau, 1986) consisted of wet sieving soil on top of a 250-μm screen 7.5 cm in diameter with a 1-cm stroke at 20 cycles per min. The soil was not pre-moistened, but plunged into room temperature deionized water at the beginning of the wet sieve process. Two grams of 1–2-mm aggregates was subjected to 30 s of sieving. In addition, 2 g of whole soil was sieved for 60 s. In the case of whole soil, the results of four subsamples were averaged. Sand can be a confounding factor in aggregate measurements (Six et al., 2000). This soil contains less than 0.01 kg kg^{-1} sand larger than 250 μm, so the presence of sand was ignored in calculating water stable aggregates.

2.4. Water percolation test

The percolation test (Auerswald, 1995) measures the rate of percolation through small soil columns under a constant head. Tubes 16-mm inner diameter with screens attached to the bottom were filled with 10 g whole soil. This soil has low clay content and weak aggregation, resulting in over 95% of the sample being less than 4-mm diameter aggregate size (Fig. 1). The 16-mm diameter tube and 10 g soil sample therefore presented no problem in producing uniform subsamples. A 2-mm layer of sand on top of the screen kept the soil from washing through the screen, and a 2-mm layer of sand, plus a loose plug of gauze, prevented water from disturbing the surface of the soil. After the soil was placed in the tube, it was dropped 2 cm onto a hard surface 10 times to pack it to a more uniform density. Deionized water poured into the tube above the soil maintained a 20-cm head. The rate of percolated water leaving the bottom of the tubes was measured for 5 min after 20 min had passed. Four subsamples were averaged for soil from each plot.

2.5. Earthworms

We counted earthworms in June during summer fallow in two of the blocks, and in December following harvest in the other two blocks. The soil was moist at both times, because of fall rain before the December sampling, and the preservation of soil moisture by fallow in the June sampling. Treatment effects and counts were very similar for the two sample dates. Cores were taken from three places in the center of all plots by driving a metal tube 20 cm in diameter 25 cm deep, and then quickly removing the core with a lever. The soil was hand sorted and a total count of mature and juvenile earthworms plus cocoons were counted. Earthworms are in very low numbers in conventional cropping systems locally, resulting in many samples with counts of zero. Therefore, the count data were transformed as the square root of the sum of the count and 0.5 before performing analysis of variance (Little and Hills, 1978). The species we have identified in cropped fields on this research station is exclusively *Apporectodea trapezoides* (Duges).

2.6. Data analysis

Many of the measurements made in this experiment are known to be affected by antecedent soil moisture (for example, aggregate stability (Gollany et al., 1991)) and perhaps previous crop conditions. Because the objective of this experiment was to search for soil factors that might explain infiltration differences caused by long-term treatments, only treatments effects are examined and effects of crop cycle are

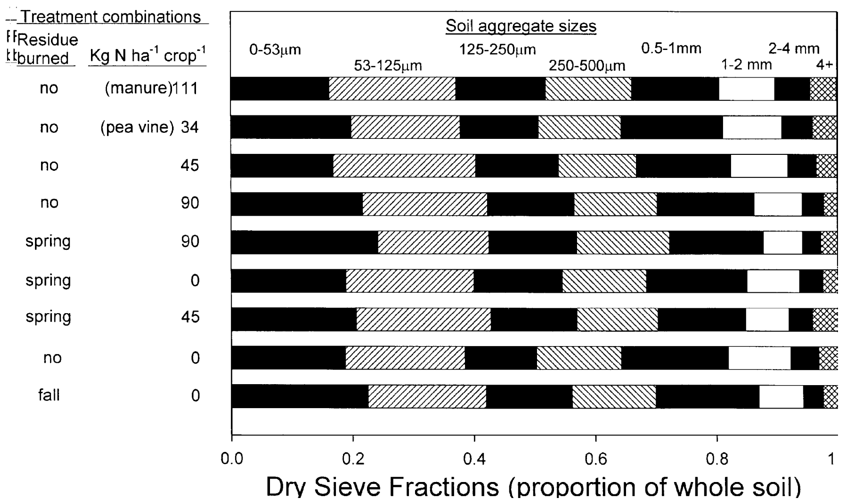


Fig. 1. Dry sieve fractions of surface soil (0–15 cm depth) graphed as proportion of whole soil.

ignored. Data presented are therefore means across the two blocks in fallow and the two blocks in winter wheat at the time the sample was taken, and statistical significance represents effects transcending block differences.

Data were analyzed using a mixed model with treatments as a fixed effect, and crop cycle, blocks within crop cycle, and treatment by crop cycle as random effects (SAS, 1998). Six treatments which represent an N rate (0, 45, 90 kg N ha^{-1}) by residue treatment (unburned versus spring burn) factorial arrangement were analyzed separately a second time to isolate N and burning effects. Again, blocking factors and interactions were treated as random effects. Linear and quadratic contrasts for the burn by N interactions were tested also. Pearson correlation coefficients were calculated for correlations between all variables (excluding runoff-precipitation ratio where only five treatments were measured). The correlations were considered statistically significant if the probability of a greater coefficient was less than 0.05 when testing against the assumption that the population correlation equaled 0. Correlations were also calculated for a subset of the data with the manure and pea vine treatments removed ($n = 7$).

3. Results

Because soil organic C is a well-recognized, quantitatively measurable trait, the treatments are ranked in order of total organic C levels in Figs. 1–4. For easier comparison the graphs are standardized. The bottom axis of each graph shows the data proportional to the unburned, 90 kg ha^{-1} treatment (which is therefore always 1.0). This treatment follows common farming practices in the region, although spring and fall burning are very common also. Actual means are indicated at the end of each bar, and units are under each graph along with analysis of variance and standard errors.

The fall burn treatment gives evidence of being the most highly degraded over the 70-year period, being lowest in C, N, water stability, and infiltration (Fig. 2). The manure and pea vine treatments (extremely unusual practices in this region) produced the highest values for most variables.

3.1. Spring burn

Spring burned versus unburned stubble in factorial combination with three N rates was analyzed as a subset of treatments. Effects of spring residue burning were statistically significant for water stability of whole soil (Fig. 2), total glomalin, basidiomycete assay on the smaller aggregates, and for earthworm counts (Fig. 3). In all cases, the burned treatments measured less on these indicators of biological activity. It is noteworthy that analysis of total C and N, despite very low standard errors, did not indicate significant burn-by-N-fertilizer effects (Fig. 2).

3.2. Infiltration and soil stability

All four measures of wet soil stability produced trends, which largely followed soil C levels (Fig. 2). Water stability of whole soil, water stability of 1–2-mm aggregates, and the percolation test on small columns were, in essence, slaking tests, since dry soil was wet rapidly. The ponded infiltration measurement, on the other hand, was performed in the field after the soil had been moist for several months.

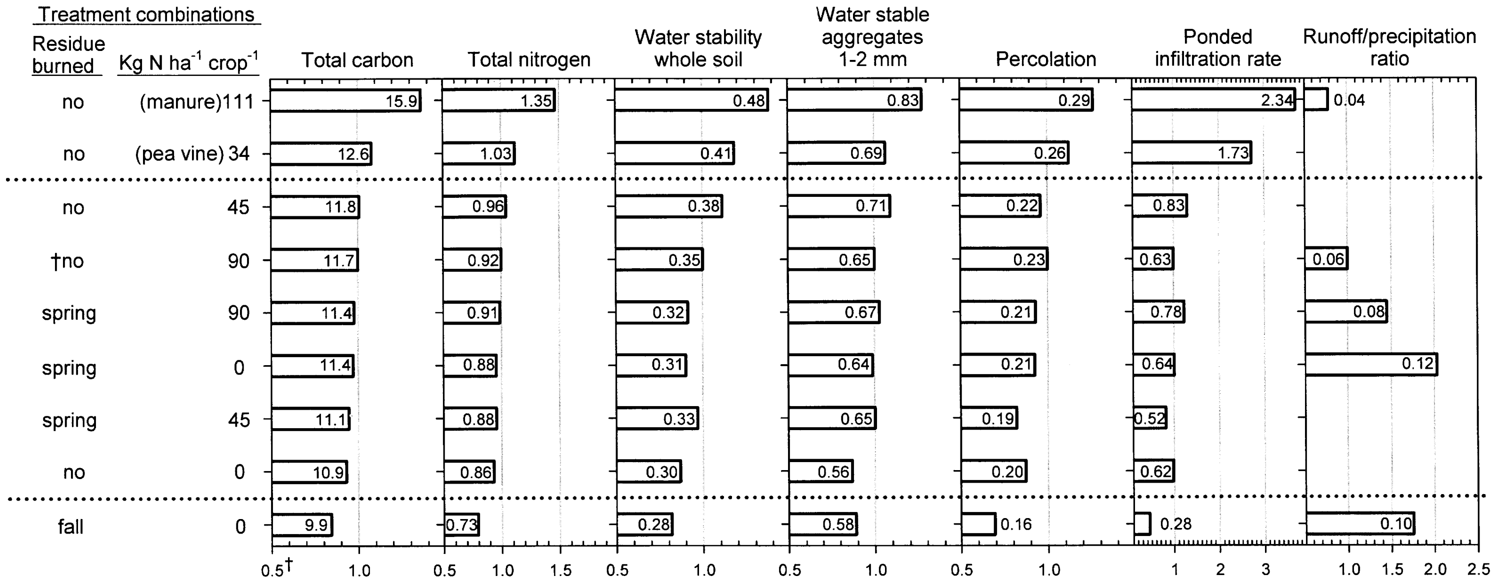
3.3. Biological contributions

Glomalin measurements follow the trend in total C. The two measures of immunoreactive glomalin (Fig. 3) show a proportionately greater response to the exogenous organic additions (pea vine and manure).

Earthworm populations were at very low levels where surface residues were burned. Pea vine and manure additions resulted in approximate doubling of earthworm populations compared to unburned treatments. The organic matter additions are plowed under soon after spreading, so the effect would necessarily be on subsurface food supply. *A. trapezoides* is often classified as endogeic, and capable of living on subsurface food sources.

3.4. Dry sieve fractions

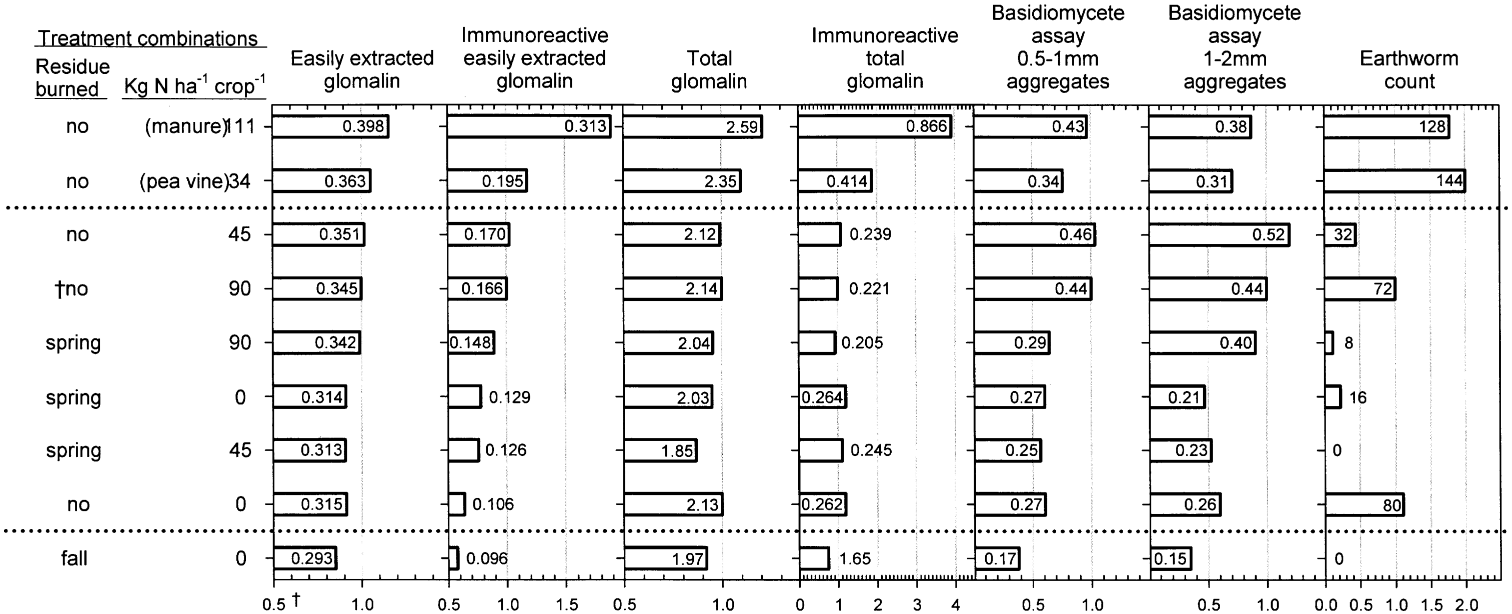
When whole soil was sieved into specific sizes, we found statistically significant effects for only three size classes (0–0.53, 0.5–1, and 1–2 mm, Fig. 4). Despite large standard errors in relation to the means, 0.5–1



		Total carbon	Total nitrogen	Water stability whole soil	Water stable aggregates 1-2 mm	Percolation	Ponded infiltration rate	Runoff/precipitation ratio
Units:		g kg^{-1}	g kg^{-1}	kg kg^{-1}	kg kg^{-1}	ml min^{-1}	mm min^{-1}	(ratio)
P>F for all treatments:		<0.0001	<0.0001	<0.0001	<0.0001	0.0029	0.0041	0.15
Standard Error:		0.043	0.004	0.075	0.108	0.025	0.793	
P>F for spring-by-N	burn	ns	ns	0.0440	ns	ns	ns	--
treatment effects	N	ns	ns	0.0033	0.0027	ns	ns	--
(between dotted lines):	burn*N	ns	ns	ns	0.0095	ns	ns	--
Standard Error:		0.045	0.003	0.073	0.108	0.023	0.482	

† All treatments are graphed in proportion to the unburned, 90 kg N ha^{-1} treatment.

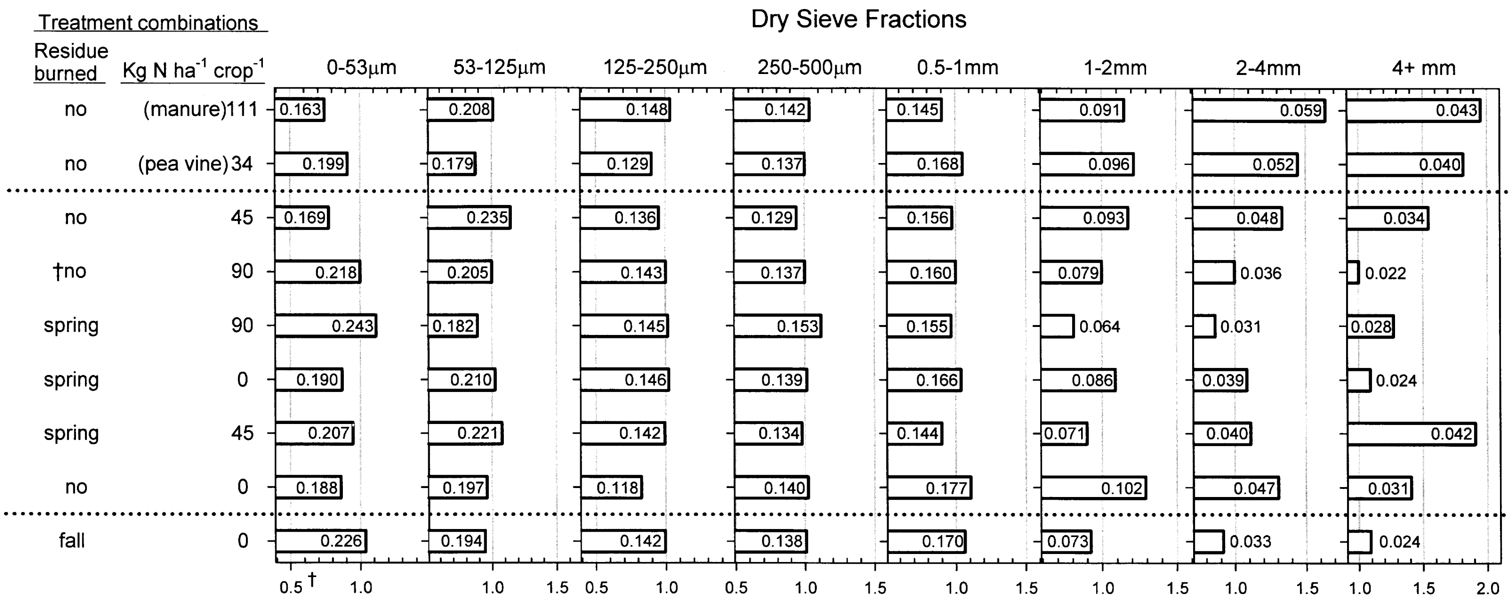
Fig. 2. Physical measurements on surface soil (0–15 cm) after 70 years of nine residue treatments in a winter wheat–fallow cropping system. Results are graphed proportional to the unburned, 90 kg N ha^{-1} treatment, which is a common practice in the region. The mean value for each treatment is shown at the end of the bars, and units are listed below the graph along with statistics for all nine treatments and for a subset of the six spring-burn-by-N treatments.



		Easily extracted glomalin	Immunoreactive easily extracted glomalin	Total glomalin	Immunoreactive total glomalin	Basidiomycete assay 0.5-1mm aggregates	Basidiomycete assay 1-2mm aggregates	Earthworm count
Units:		mg g^{-1}	mg g^{-1}	mg g^{-1}	mg g^{-1}	absorbance‡	absorbance‡	m^{-2}
P>F for all treatments:		0.0002	0.0093	<0.0001	<0.0001	0.0110	ns	ns
Standard Error:		0.013	0.028	0.105	0.049	0.063	0.103	1.33
P>F for spring-by-N	burn	ns	ns	0.0219	ns	0.0273	ns	0.0590
treatment effects	N	ns	ns	ns	ns	ns	ns	ns
(between dotted lines):	burn*N	ns	ns	ns	ns	ns	ns	ns
Standard Error:		0.013	0.023	0.112	0.051	0.064	0.122	0.878

†All treatments are graphed in proportion to the unburned, 90 kg N ha^{-1} treatment.
‡Absorbance at 450 nm.

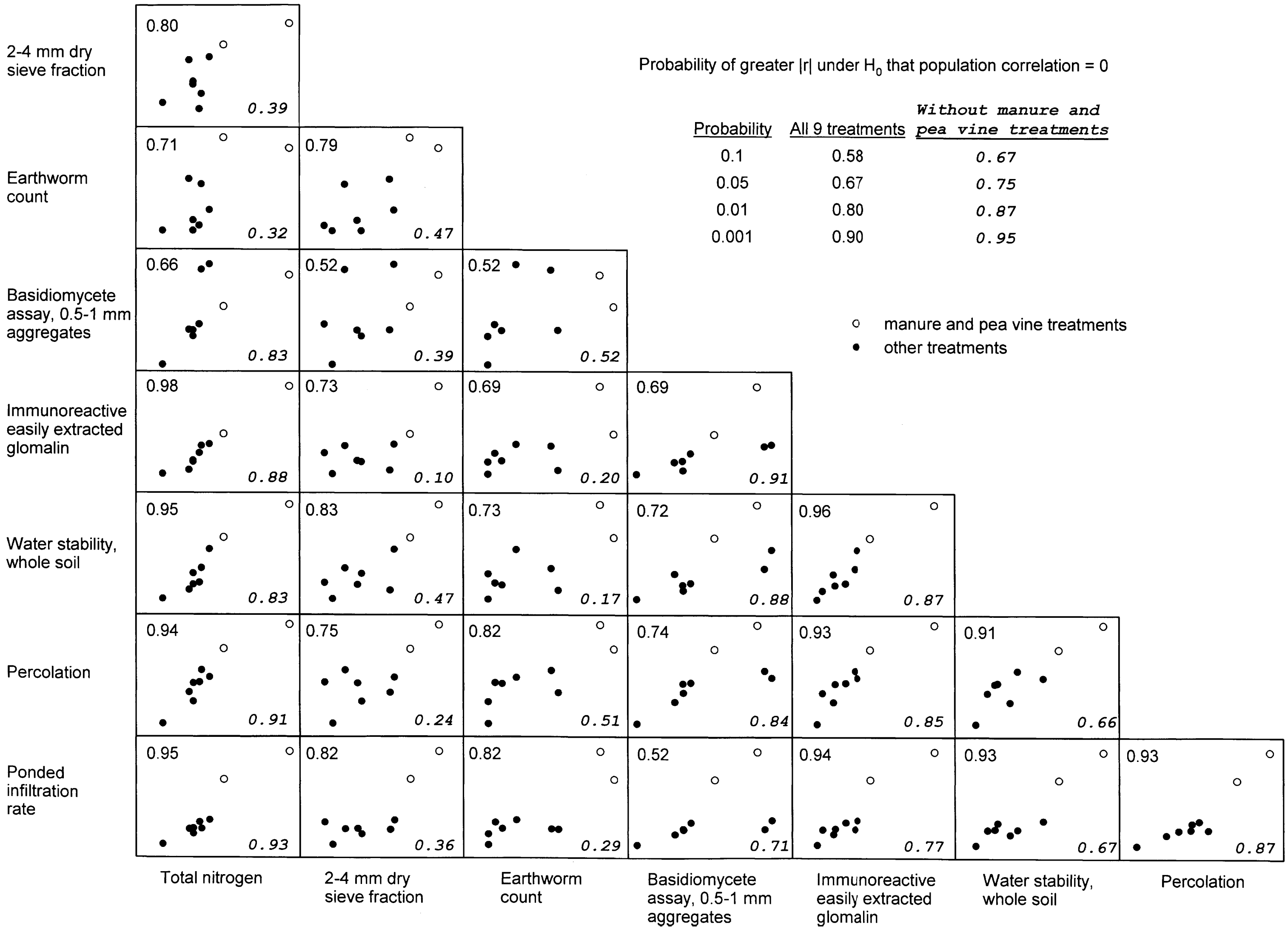
Fig. 3. Biological measurements on surface soil (0–15 cm) after 70 years of nine residue treatments in a winter wheat–fallow cropping system. Results are graphed proportional to the unburned, 90 kg N ha^{-1} treatment. The mean value for each treatment is shown at the end of the bars, and units are listed below the graph along with statistics for all nine treatments and for a subset of the six spring-burn-by-N treatments.



		0-53µm	53-125µm	125-250µm	250-500µm	0.5-1mm	1-2mm	2-4mm	4+ mm
Units:		kg kg^{-1}							
P>F for all treatments:		ns	ns	ns	ns	ns	ns	ns	ns
Standard Error:		0.035	0.036	0.015	0.025	0.052	0.016	0.011	0.010
P>F for spring-by-N	burn	ns	ns	ns	ns	0.0449	0.0013	ns	ns
treatment effects	N	0.0410	ns	ns	ns	0.0028	0.0043	ns	ns
(between dotted lines):	burn*N	ns	ns	ns	ns	ns	ns	ns	ns
Standard Error:		0.033	0.042	0.018	0.026	0.056	0.017	0.010	0.009

†All treatments are graphed in proportion to the unburned, 90 kg N ha^{-1} treatment.

Fig. 4. Dry sieve fractions (0–15 cm surface soil) graphed proportional to the unburned 90 kg N ha^{-1} treatment. The mean value for each treatment is shown at the end of the bars, and units are listed below the graph along with statistics for all nine treatments and for a subset of the six spring-burn-by-N treatments.



Probability	All 9 treatments	*Without manure and pea vine treatments*
0.1	0.58	0.67
0.05	0.67	0.75
0.01	0.80	0.87
0.001	0.90	0.95

Fig. 5. Scatter–plot matrix of eight variables. Open symbols are the manure and pea vine treatments. Correlation coefficient for all nine treatments is shown in upper left corner, and correlation coefficient for seven treatments (removing manure and pea vine) is shown in the lower right corner.

and 1–2 mm fractions demonstrated responses to burning and N treatments when the six burn-by-N treatments were analyzed separately. In both cases burning produced fewer aggregates. The significant N effect for these two size classes indicates fertilizer additions might have a detrimental effect on aggregate formation, since the zero N treatments had more aggregates than 45 and 90 kg N. The opposite effect is seen in the non-aggregated <53 μm class, which makes sense because the total of all fractions must add up to 1. Soil aggregates larger than 1 mm make up a very small proportion of the whole soil. Fig. 1 gives a better representation of the proportion of each size class to whole soil.

3.5. Selection of variables for correlation

Seven variables were chosen for correlation with ponded infiltration and with each other based on the number and degree of correlation they displayed in a comparison of all possible correlations of 21 measured variables (Fig. 5). Correlation coefficients were calculated twice, once for all nine experimental treatments, and once with the manure and pea vine treatments removed ($n = 7$). In some cases it is obvious that the correlation using all nine treatments is highly influenced by these two extreme treatments, and that the other seven treatments alone do not indicate significant correlation of the variables.

In choosing variables for Fig. 5, total N was chosen over total C, because they follow each other very closely ($r = 0.997$ when $n = 9$, $r = 0.981$ when $n = 7$), but total N had slightly higher correlation coefficients for a majority of variables. Water stability of whole soil and percolation had greater numbers of significant correlations with other variables than water stable aggregates of 1–2 mm, and were chosen for Fig. 5. Basidiomycete assay on 0.5–1-mm aggregates had better correlations than the same assay on 1–2-mm aggregates.

Total glomalin and immunoreactive total glomalin maintained only one statistically significant correlation ($r = 0.80$ between total glomalin and earthworm count) when manure and pea vine treatments were eliminated, whereas easily extracted glomalin and immunoreactive easily extracted glomalin maintained 9–12 statistically significant correlations after eliminating manure and pea vine treatments. Immunoreactive easily extracted glomalin was chosen for Fig. 5 because it had slightly higher correlation coefficients.

The dry sieve fraction of 2–4 mm was the only dry sieve fraction with more than two correlations with the other 20 variables significant at $p < 0.05$. (The >4-mm fraction had $r = 0.67$ with ponded infiltration rate and $r = 0.71$ with water stability of whole soil.) The 12 significant correlations between 2- and 4-mm dry sieve fraction and other variables dropped to 5 when the manure and pea vine data were eliminated, and 4 of these were with other dry sieve fractions. The 2–4-mm dry sieve fraction is included in Fig. 5. (Franzluebbers et al. (2000) also found a lack of relationship between dry aggregates and water stable aggregates.)

3.6. Correlations

Ponded infiltration rate is well correlated with total N and percolation, both including and excluding the manure and pea vine treatments (bottom row of Fig. 5). Immunoreactive easily extracted glomalin and water stability of whole soil are also reasonably well correlated with ponded infiltration rate. The 2–4-mm dry sieve fraction and earthworm count are both poorly correlated with ponded infiltration rate without the extreme values from the manure and pea vine treatments.

The basidiomycete assay (on 0.5–1-mm aggregates) produced scatter plots that indicate three treatment groupings (fourth column and third-from-top row, Fig. 5). Manure and pea vine treatments produced the highest values for all variables but the basidiomycete assay. The unburned 45 and 90 kg N treatments produced the highest values in the basidiomycete assay, and the remaining treatments (burned or no N addition) form a group that is medium-to-low for all variables. The presence of three well-separated groups prevents confidence that the correlation coefficients are measuring true, continuous relationships of the two variables being examined.

4. Discussion

The treatment extremes produced by manure and pea vine additions are of interest in terms of the capacity of this soil in this climate to respond to management variables (Figs. 2 and 3). Manure and pea vine treatments were responsible for highly significant differences for all but Basidiomycetes on 1–2-mm aggregates, earthworm counts, and dry sieve fractions. Of greater agronomic interest is the potential for more common management differences to change soil qualities in the long-term. Eight of the 22 variables had significant effects within the burn-by-N treatment subset (Figs. 2–4). Total C and N measurements, however, did not produce significant burn-by-N-fertilizer effects despite very low standard errors. It is possible that total C has responded more slowly to the management changes made 34 and 22 years ago (Table 1), resulting in some differences in ranking compared to parameters which respond more quickly. An alternative explanation is that total C and N are relatively more responsive to root-derived organic matter. The excellent correlation between measures of easily extracted glomalin and total C and N indicates that long-term accumulation might be related to glomalin-producing arbuscular mycorrhizal fungi (Wright and Upadhyaya, 1998), and therefore have little dependence on surface residues.

Aggregates have greater water stability if they are wet gradually before wet sieving (Haynes and Fraser, 1998). This experiment is located in a climate where soils become very dry during the summer and then are remoistened by fall rains. Rainfall intensity and drop size in this region are insufficient to physically break down aggregates (McCool et al., 1982), but slaking occurs as aggregates are wetted, leading to surface crusts. This sealing accounts for 13% or more of the regional runoff, the other 87% is related directly to frozen soil events (Williams, 2004; Zuzel et al., 1982). Actual field conditions, as measured by ponded infiltration rates and runoff/precipitation ratio, appear to amplify differences in aggregate stability measured in the laboratory (Fig. 2).

Since the ponded infiltration was performed on all plots at the same time, half of the plots were in stubble and the other half in winter wheat crop at the time of measurement. Therefore, effects of macropores developed by roots and crowns or earthworms in the stubble-covered plots are reflected in ponded infiltration rates. The three- to four-fold increase in infiltration in the pea vine and manure treatments might be related to macropores produced by the two-fold greater earthworm population. None of these macropore features would be reflected in laboratory measurements, which were performed on disturbed soil.

Pikul and Allmaras (1986) reported that in these plots, the zone just below the depth of plowing was the most restrictive layer for water flow. The flow rates they report, however, are far lower than those we have measured. Their K_{sat} estimates range from 0.83 mm h^{-1} in the tillage pan (23 cm depth) using a double tube method with tubes of 10 and 20 cm diameter to 14.9 mm h^{-1} on a stubble covered surface using an air-entry permeameter and rejecting samples with non-uniform wetting fronts. Using cylinders of 20–47 cm diameter driven to 25 cm depth, we measured steady-state ponded infiltration rates from less than 1 to over 200 mm h^{-1} in individual replicates. Our rings were larger and our data include both uniform and non-uniform (preferential) flow. It appears that our lowest readings are comparable to their K_{sat} estimates, but our more typical readings were much greater. The investigation into the effect of ring diameter is ongoing, but it appears that preferential flow plays an important role in infiltration even in tilled soil.

Immunoreactive glomalin is currently considered to be the glomalin fraction most similar to the highly immunoreactive glomalin found on hyphae (Wright et al., 1996; Wright and Upadhyaya, 1998). Franzluebbers et al. (2000) measured higher glomalin levels in surface soil under grazing versus haying in a grass field. It is possible that organic amendments indirectly stimulate glomalin production through better soil moisture retention. This could explain the disproportionate response of immunoreactive glomalin to the manure treatment (Fig. 3) compared to total C (Fig. 2). In contrast to glomalin, soil-aggregating basidiomycete populations are favored by certain residue treatments over others, regardless of total soil organic C levels. These organisms utilize lignin in wheat residues as a C source for growth. While all of the treatments received wheat residues, where most of the surface residue was burned off in the fall after harvest or in the spring before plowing basidiomycete populations were lower. It also appears that manure and pea vine additions do not support increased populations of these specific organisms, and may even depress them slightly.

5. Conclusions

Interpretation of the data is complicated by the fact that four of the nine treatments have only been in place in their current form for 22–34 years. This should be long enough to reach equilibrium levels in terms of yield and soil carbon and nitrogen fractions with relatively rapid turnover, but perhaps not long enough for factors with very slow turnover rates. Since our objectives were to discover what soil factors allow high infiltration rates, the treatments producing those infiltration differences are of less importance but will be discussed also using the assumption that 22 years has been long enough to properly attribute soil properties to current treatments.

Our data indicate that differences in ponded infiltration rates in this experiment are correlated with organic C and N, aggregate stability and glomalin measurements. Of these, water stability of whole soil and water stable aggregates of 1–2 mm were the only measures to show significant effects of N applications or burning. Percolation, the third measure of aggregate stability, was not affected by burning or N treatments but demonstrated excellent correlation to ponded infiltration rate, second only to total N (and C).

Immunoreactive easily extracted glomalin was highly correlated ($r = 0.98$) with total N and C, which might indicate that arbuscular mychorrizae are major contributors to long-term C accumulation. Burning significantly reduced the measure of total glomalin, but neither burning nor N treatments produced effects on the other three-glomalin assays. Since burning and N treatments definitely affect above-ground residue production and the amount of residue incorporated into the soil, it appears that surface residues have much less influence on total C over long periods.

Basidiomycete populations were greater where wheat residue was not burned, but did not follow overall trends in aggregate stability since they did not respond to the pea vine and manure treatments. Earthworm populations were very low where residues were burned, but might have played a role in infiltration in pea vine and manure treatments. This might partly explain why infiltration rates are disproportionately high compared to many other soil factors for those two treatments.

Significant effects of N fertilizer rate were found for only 5 of the 22 variables measured, and 3 of those were dry sieve fractions. The 0.5–1 and 1–2-mm dry sieve fractions were smaller proportions of the soil with 45 and 90 kg ha^{-1} N than with zero N. The opposite is true of water stability of whole soil and water stable aggregates of 1–2 mm.

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