Macroaggregate Characteristics in Cultivated Soils after 25 Annual Manure Applications

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ABSTRACT

Agricultural management practices that alter the soil organic matter (SOM) content are expected to cause changes in soil stability and aggregation. Animal manure is a source of organic matter (OM) that has been demonstrated to increase macroaggregate formation and stability. The objectives of this study were to determine how long term cattle manure applications to a calcareous Haploboroll clay loam (Lethbridge, AB, Canada) affected aggregate size distribution, the total C, N, and P content of aggregate size fractions, and water-stable aggregates. Beef cattle manure applied at rates >30 Mg ha^{-1} yr^{-1} under dryland production and >60 Mg ha^{-1} yr^{-1} to soils under irrigation resulted in fewer dry-sieved aggregates >7.1 mm and more dry-sieved aggregates between 0.47 and 1.2 mm in the 0- to 5-cm depth, compared with unamended soils. The dry-sieved aggregate fractions between 0.47 and 1.2 mm include the <0.84-mm fraction that has been associated with increased susceptibility to wind erosion in the Canadian semiarid prairies. There was more total C, N, and P in all dry-sieved aggregate fractions of soils receiving >30 Mg manure ha^{-1} yr^{-1} than unamended soils, and dry-sieved aggregates between 0.47 and 2.0 mm tended to have the highest C, N, and P contents. Water aggregate stability was higher in irrigated than dryland soils, but did not improve with increasing manure application rates. Dispersing agents in the cattle manure appear to have destabilized the larger soil macroaggregates.

The application of animal manure to agricultural land has been viewed as an excellent way to recycle nutrients and OM that can support crop production and maintain or improve soil quality. Generally, SOM and biological activity increase, and some soil physical properties improve following manure applications (Haynes and Naidu, 1998). A variety of soil physical properties, including bulk density, water holding capacity, aggregation, surface crusting, infiltration capacity, and hydraulic conductivity may be influenced by animal manure (Hafez, 1974; Khaleel et al., 1981; Sommerfeldt and Chang, 1985; Sommerfeldt et al., 1988; Haynes and Naidu, 1998). Aggregation is perhaps one of the most important physical properties affected by OM additions because stable soil aggregates have a beneficial influence on soil moisture status, nutrient dynamics, soil tilth maintainence, and soil erosion reduction (Allison, 1973; Oades 1984).

It is well known that cultivation reduces SOM content and changes the distribution and stability of soil aggregates. Macroaggregates are disrupted, and soils become more susceptible to erosion as cultivation intensity increases, which can contribute to a further loss of SOM (Elliott, 1986; Cambardella and Elliott, 1993; Beare et al., 1994; Six et al., 2000a). Long-term applications of animal manure increase the SOM content in two ways: (i) by adding OM in manure (Sommerfeldt and Chang, 1985) and (ii) by adding OM in crop residues, due to higher crop yields in soils receiving manure (Jenkinson and Rayner, 1977; Angers and N'Dayegamiye, 1991). One year after manure application, Sun et al. (1995) found a significantly higher proportion of water stable macroaggregates (1–2 mm) in eroded soils treated with cattle, hog, or poultry manure, compared with unamended soils. The proportion of water stable macroaggregates (>0.25 mm) increased in soils that received annual cattle manure applications for more than a decade (Angers and N'Dayegamiye, 1991; Aoyama et al., 1999). The decomposition rate of animal manure is expected to affect macroaggregate formation. Organic materials that decompose quickly may produce a rapid increase in aggregation, but the effect may be temporary; whereas organic materials that decompose slowly may produce a smaller but longer-lasting improvement in aggregation (Khaleel et al., 1981; Sun et al., 1995). Aoyama et al. (1999) proposed that animal manure applications increase the particulate OM pool and promote macroaggregate formation in the short-term, whereas in the longer-term, manure may be transformed into mineral-associated OM that can improve microaggregate stability.

Despite the benefits to soil aggregation from applying animal manure to cultivated soils, long-term manure applications can contribute to nutrient accumulation, particularly P, in agricultural soils. As P accumulates in soil, the risk of P transport to water bodies through erosion, leaching, and runoff processes increases (Sharpley et al., 1994; Lennox et al., 1997; Whalen and Chang, 2001). Improvements in soil aggregation from manure might reduce P transport from agricultural soils through reduced erosion, but there are conflicting reports on the distribution of P and other nutrients in macroaggregates from cultivated, manure-amended soils. It is unclear whether the aggregates most prone to erosion are enriched with P and other nutrients. Some researchers have found that manure applications lead to higher concentrations of total C, N, and P in dry-sieved macroaggregates >0.25 mm than in microaggregates and more total C and N in water-stable aggregates >0.053 mm (Bhatnagar et al., 1985; Bhatnagar and Miller, 1985; Mbagwu and Piccolo, 1990; Aoyama et al., 1999). However, other workers have reported higher concentrations of organic C and total P in microaggregates <0.1 mm than in macroaggregates (He et al., 1995; Wan and El-Swaify, 1996; Maguire et al., 1998). Clearly, further work is needed to identify how nutrients added in manure are distributed among soil aggregate fractions, the sta-

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Abbreviations: OM, organic matter; SOM, soil organic matter.

bility of those aggregate fractions to erosion, and the potential for nutrient release from eroded aggregates if they are transported into aquatic environments.

The objectives of this study were to determine the effect of long term manure applications on (i) aggregate size distribution, (ii) the total C, N, and P content of aggregate size fractions, and (iii) water-stable aggregates.

MATERIALS AND METHODS

Soils used in this study were from research plots located at the Lethbridge Research Center in southern Alberta, Canada. Since 1973, solid cattle feedlot manure has been applied annually to dryland and irrigated soils in a split-plot experiment. The soil in the study area is a well-drained calcareous Typic Haploboroll (orthic dark brown chernozemic) clay loam, and from 1974 to 1995 was cropped annually with 6-row feed barley (*Hordeum vulgare* L. 'Galt', 'Leduc', 'Virden' and 'Duke'). All plots were seeded with canola (*Brassica rapa* L. 'Tobin') in 1996, and the dryland plots were seeded with barley (*H. vulgare* L. 'Duke') in 1997, and triticale (× *Triticosecale* 'Pronghorn') in 1998 and 1999. The irrigated plots were cropped with corn (*Zea mays* L. 'Pioneer Hybrid 3957') from 1997 to 1999. Further details of the research site and the effect of long-term manure amendments on soil chemistry, fertility, nutrient balance, and physical properties have been reported (Sommerfeldt and Chang, 1985; Chang et al., 1991, 1993; Chang and Janzen, 1996; Whalen and Chang, 2001).

Experimental Design

Solid feedlot manure was applied each fall after harvest, beginning in 1973 and incorporated immediately after application by one of three methods: plow, rototiller, or cultivator plus disk. Within each tillage treatment (main plot), manure was applied to subplots (7.5 by 15 m) at the following rates: 0, 30, 60, and 90 Mg ha^{-1} (wet weight) in dryland soils and 0, 60, 120, and 180 Mg ha^{-1} (wet weight) in irrigated soils. Main and subplot treatments were assigned randomly and replicated three times. At the initiation of the experiment, recommended annual manure applications in this area were 30 Mg manure (wet weight) ha^{-1} for dryland soils and 60 Mg ha^{-1} (wet weight) for irrigated soils (Alberta Agriculture, 1980). Soil properties and crop production were not affected significantly by tillage (Sommerfeldt et al., 1988; Chang et al., 1990). Since 1986, manure has been incorporated in all subplots with a cultivator, which increased the number of replicate manure treatments to nine. In 1986, manure applications to three plots that were originally rototilled in the dryland and irrigated treatments were stopped to evaluate the residual effects of manure on soil properties and crop production. We investigated macroaggregate characteristics on the six replicate plots that received manure every year from 1973 to 1998, inclusive.

Manure applied in this study from an open, unpaved commercial cattle feedlot, contained no bedding, and was stored 1 to 2 yr before application. Manure characteristics varied from year to year, although the manure applied in a given year was from the same source (Chang et al., 1991). Manure applied between 1973 and 1998 contained, on average (±SE), 133 ± 8 g C kg^{-1} (dry combustion), 16 ± 1 g N kg^{-1} (Kjeldahl N), 6.2 ± 0.3 g P kg^{-1} (Na_2CO_3-fusion), and 0.33 ± 0.02 kg H_2O kg^{-1} manure (oven dried at 105°C for 48 h).

Aggregate Size Distribution and Carbon, Nitrogen, and Phosphorus Content

Soil samples were collected in the fall of 1999 after harvest, but before manure application. Two 38 cm × 38 cm × 15 cm (deep) pits were dug near the center of each plot, between crop rows. Soil blocks removed from the pits were divided into two depths (0- to 5-cm and 5- to 15-cm depths), and a composite sample was made by carefully combining the soil from each depth increment. The mean gravimetric water content was 0.078 ± 0.003 kg kg^{-1} in the 0- to 5-cm depth and 0.088 ± 0.004 kg kg^{-1} in the 5- to 15-cm depth at the time soils were sampled. Soils were air-dried and carefully placed into a rotary sieve to minimize disturbance to the aggregates. The rotary sieve separated the samples into seven different size fractions, namely <0.47 mm, 0.47 to 1.2 mm, 1.2 to 2 mm, 2 to 7.1 mm, 7.1 to 12.7 mm, 12.7 to 38 mm, and >38 mm, based on the method of Chepil and Bisal (1943). A composite, unground, aggregate sample (≈10 g) from each of the seven size fractions was made for every soil depth and manure treatment sampled in the two irrigation blocks. The composite aggregate samples were analyzed for sand, silt, and clay content using the hydrometer method (Day, 1965). The sand content of aggregates from the dryland block was, on average (±SE), 273 ± 5 g kg^{-1} (0 to 5 cm) and 291 ± 5 g kg^{-1} (5 to 15 cm). In the irrigated block, the average (±SE) sand content of aggregates was 295 ± 5 g kg^{-1} (0 to 5 cm) and 297 ± 5 g kg^{-1} (5 to 15 cm). After recording aggregate weights in each size fraction for each soil sample, a portion of the aggregates were oven-dried (60°C for 48 h) and finely ground (<150 μm) for total C, N, and P analysis. Total C and N in aggregate fractions were determined on a Carlo-Erba C and N Analyzer (Milan, Italy). Total P in aggregate fractions was determined using the wet digestion method of Parkinson and Allen (1975). Briefly, 1 g of the sample was weighed into a digestion tube and digested at 360°C for 2.5 h with concentrated H_2SO_4, Li_2SO_4, Se powder, and H_2O_2. Phosphorus in digests was analyzed colorimetrically by the ammonium molybdate-ascorbic acid method (Murphy and Riley, 1962) using a Technicon IV autoanalyzer (Technicon Industrial Systems, Tarrytown, NY).

Wet Aggregate Stability

The stability of aggregates from the 0- to 5-cm and 5- to 15-cm depths of each plot was determined by wet-sieving the 1.2- to 2-mm aggregate fraction by a modification of the Kemper and Rosenau (1986) wet-sieving method. About 4 g of air-dried aggregates from the 1.2- to 2-mm fraction were weighed onto a sieve (0.26 mm) and slowly prewetted to a water content of 0.07 to 0.09 kg kg^{-1} by placing the sieve over a deionized water vapour steam for 22 h. Each sieve was sealed in an airtight container and allowed to equilibrate overnight (≈16 h). Aggregates were then sieved in deionized water for 5 min using an apparatus with a stroke length of 1.3 cm and a frequency of 35 cycles min^{-1}. The material passing through the sieve (unstable aggregates) was oven-dried at 110°C for 48 h. Sand particles >0.26 mm were separated from the material remaining on the sieve by dispersion for 2 min with a probe-type sonifier (Branson Sonifier Model 250, Branson Ultrasonics Corporation, Danbury, CT) with an input energy of 2000 J, rinsed with deionized water. The material passing through the sieve (stable, sand-free aggregates) was then oven-dried. Aggregate stability was the mass of stable aggregates divided by the total aggregate (stable + unstable) mass, and expressed as the percentage of water-stable aggregates (sand-free aggregate basis).

Statistical Analysis

There was only one block each of dryland and irrigated land, which were under different cropping regimes in 1999, so it was not possible to compare the results between the two irrigation regimes statistically. The mass of dry-sieved aggregates in each size fraction were influenced significantly by soil depth in the dryland block ($P < 0.01$) and the irrigated block ($P < 0.002$). The effect of manure on dry-sieved aggregate distributions for each soil depth was evaluated statistically by one-factor ANOVA in a general linear model using SAS software (SAS Institute, 1990). The effect of manure and aggregate size on the distribution of total C, N, and P in soils from each depth of the dryland and irrigated blocks was evaluated statistically by two-factor ANOVA. A protected least-significant difference (LSD) test ($P < 0.05$) was used to determine the significance of main effects from ANOVA. Wet aggregate stability in the 1.2- to 2.0-mm aggregate fraction was not affected significantly ($P > 0.05$) by soil depth or manure application, and results presented are the arithmetic means and standard errors.

RESULTS

Dry-Sieved Aggregate Size Distribution

In the 0- to 5-cm depth of dryland soils, the largest proportions of dry-sieved aggregates were <0.47 mm, and soils amended with 60 and 90 Mg manure ha^{-1} yr^{-1} had significantly fewer dry-sieved aggregates >12.7 mm and significantly more dry-sieved aggregates <2.0 mm than unamended soils (Fig. 1). The majority of dry-sieved aggregates in the 5- to 15-cm depth of dryland soils were >12.7 mm (Fig. 1). Soils amended with 30 and 90 Mg manure ha^{-1} yr^{-1} had significantly more dry-sieved aggregates between 2.0 and 0.47 mm than unamended soils (Fig. 1). Similar trends were observed in soils from the irrigated block. In the 0 to 5 cm of irrigated soils, there were significantly fewer dry-sieved aggregates >7.1 mm, and significantly more dry-sieved aggregates <2.0 mm in the 0 to 5 cm of soils amended with 120 and 180 Mg manure ha^{-1} yr^{-1} than unamended soils (Fig. 2). In the 5- to 15-cm depth of irrigated soils, there were significantly more dry-sieved aggregates <2.0 mm in the 120 and 180 Mg ha^{-1} yr^{-1} treatments than unamended soils (Fig. 2).

In the semiarid prairies, the proportion of soil mass <0.84 mm has been identified to be prone to wind erosion (Campbell et al. 1993; Larney et al., 1994b). The dry-sieved aggregate fractions at risk of erosion from this study include a portion of the 1.2- to 0.47-mm fraction and the <0.47 mm fraction. We did not separate the 1.2- to 0.47-mm fraction into aggregates larger than 0.84 mm, and so will refer to aggregate fractions <1.2 mm in the 0- to 5-cm depth of soil to be at risk of wind erosion (Fig. 1, 2). Clearly, we will overestimate the mass of soil that may be wind erodible due to the limitations of our data. Between 34 and 43% of soil in dryland plots was at risk of erosion, and the risk was greater in soils amended with 60 and 90 Mg manure ha^{-1} than unamended soils. In irrigated plots, between 18 and 43% of soil was at risk of erosion, and there was a greater risk in soils receiving long term applications of 120 and 180 Mg manure ha^{-1}.

Total Carbon, Nitrogen, and Phosphorus Contents of Dry-Sieved Aggregate Fractions

Dry-sieved aggregates separated from the 0- to 5-cm depth of dryland and irrigated plots that received manure applications of ≥60 Mg ha^{-1} yr^{-1} had significantly more total C, N, and P than unamended soils (Fig. 3, 4, 5). Similar trends were observed in the aggregates separated from the 5- to 15-cm depth of dryland and irrigated plots (data not shown). We present the total C, N, and P in the aggregate fractions <12.7 mm in size; aggregates >12.7 mm contained similar quantities of nutrients as those in the 7.1- to 12.7-mm aggregate fraction.

There was no difference in the total C and N of aggregate fractions from the 0- to 5-cm depth of dryland soils (Fig. 3 and 4). In dryland soils amended with 90 Mg ha^{-1} yr^{-1}, aggregates <0.47 mm had significantly less total P than aggregates between 0.47 and 7.1 mm (Fig. 5). In the 0- to 5-cm depth of irrigated soils amended with 60 Mg ha^{-1} yr^{-1}, the total C, N, and P contents were significantly lower in aggregates <0.47 mm than aggregates between 0.47 and 2.0 mm (Fig. 3, 4, 5). There was less total C, N, and P in the aggregates <0.47 mm than aggregates between 0.47 and 2.0 mm in irrigated soils (0- to 5-cm depth) amended with 120 and 180 Mg ha^{-1} yr^{-1} (Fig. 3, 4, 5).

Wet Aggregate Stability

In semiarid areas like those examined in this study, water content of surface aggregates is quite likely to range from air dry to 0.11 kg water kg^{-1} soil aggregate (Sun et al., 1995). Wet aggregate stability was determined after slowly wetting the dry-sieved aggregates from the 1.2- to 2.0-mm fraction to between 0.07 and 0.09 kg kg^{-1}. Wet aggregate stability in the 0- to 15-cm depth, expressed as the percentage water stable, sand-free aggregates, ranged from 56 to 82% in dryland soils and 80 to 91% in irrigated soils, and tended to be higher in manure-amended than unamended soils (Table 1).

DISCUSSION

The distribution of dry-sieved aggregates differed among the two soil depths, and the proportion of dry-sieved aggregates <1.2 mm in diameter was 41 to 65% higher in the 0- to 5-cm than the 5- to 15-cm increment of dryland soils. There were 58 to 72% more dry-sieved aggregates <1.2 mm in the 0 to 5 cm of irrigated soils than the 5- to 15-cm soil depth. It is not surprising that the proportion of dry-sieved aggregates <1.2 mm was greater in the 0- to 5-cm fraction than deeper in the soil profile of dryland and irrigated plots. Aggregates closest to the soil surface were likely disrupted mechanically by tillage and by farm vehicles used to irrigate and harvest the plots to a greater extent than aggregates located deeper within the soil matrix. Other studies in the semiarid prairies of western Canada have found aggregates in the top 2.5 to 5 cm of soil are made unstable through freezing and thawing, wetting and drying, and freeze-drying, and the wind-erodible fraction of soil is generally considered to be the unstable aggregates with a diameter <0.84 mm from the top few centimeters of soil (Campbell et al., 1993; Larney et al., 1994a; Sun et al., 1995). The fraction of soil in dryland and irrigated plots at risk of wind erosion, based on the proportion

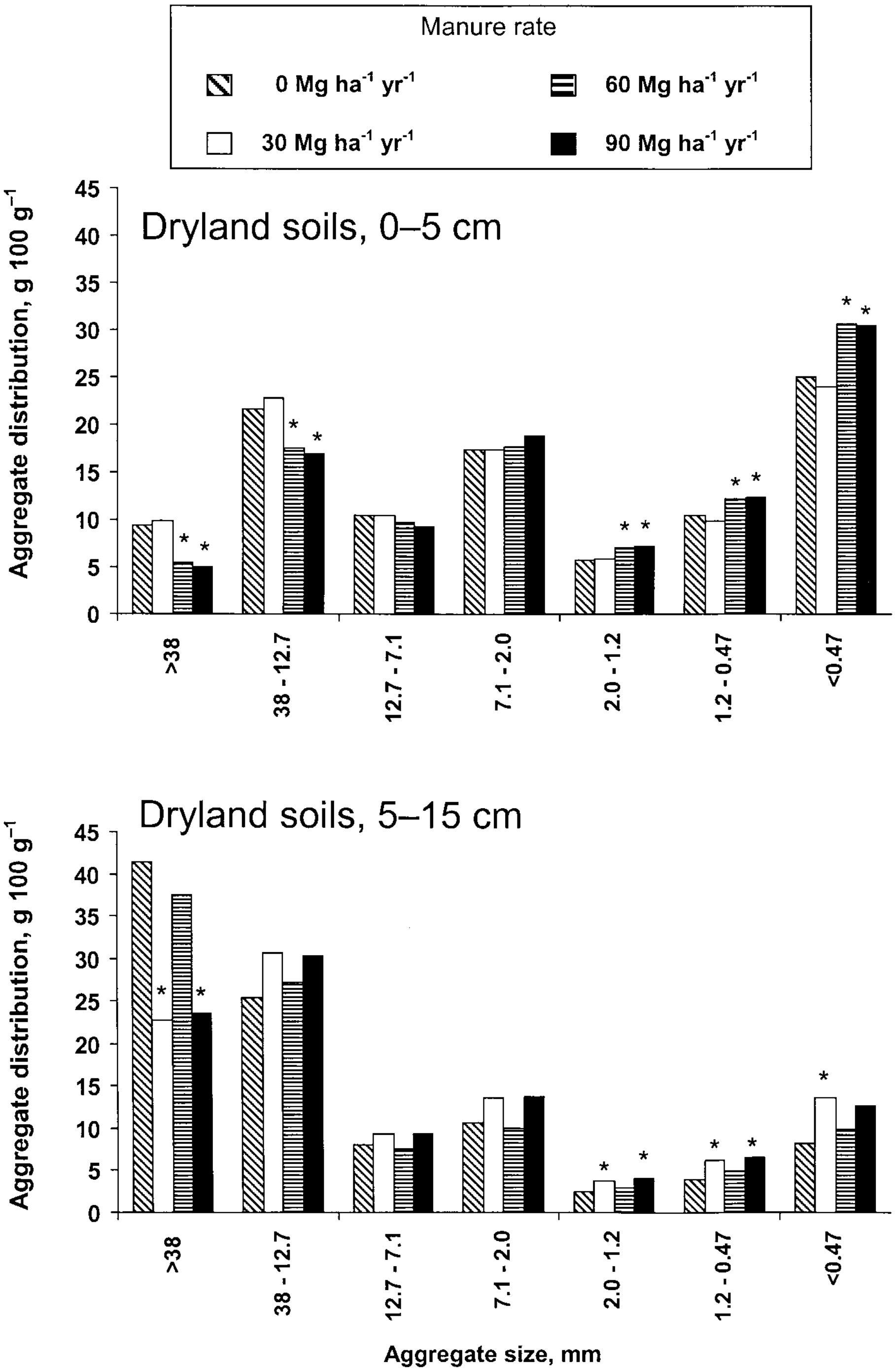

Fig. 1. Aggregate size distribution in the 0- to 5-cm layer and the 5- to 15-cm layer of dryland plots. Bars with asterisks denote an aggregate distribution that was significantly different ($P < 0.05$, LSD) from unamended plots (0 Mg manure ha^{-1} yr^{-1}).

of dry-sieved aggregates <1.2 mm in the 0- to 5-cm soil layer, was as high as 43% of the soil mass.

Long-term manure applications affected the dry-sieved aggregate size distribution, particularly in the 0- to 5-cm soil depth, and the wind-erodible fraction of soil significantly. Applications of 60 and 90 Mg ha^{-1} yr^{-1} of cattle feedlot manure shifted the aggregate distribution in the 0 to 5 cm of dryland soils from very large (>12.7 mm) to smaller (<2.0 mm) dry-sieved aggregates. Similarly, there was a decline in the proportion of dry-sieved aggregates >7.1 mm and an increase in dry-sieved aggregates <2.0 mm in the 0- to 5-cm layer of irrigated soils that received 120 and 180 Mg manure ha^{-1}. Consequently, the fraction of soil at risk of wind erosion was greater in dryland soils amended with 60 and 90 Mg manure ha^{-1}, and in irrigated soils amended with 120 and 180 Mg manure ha^{-1}, than unamended soils. Although there appears to be greater potential for soil loss from sites amended with higher rates of manure for many years, erosion measurements from field or wind tunnel experiments are needed to confirm this possibility.

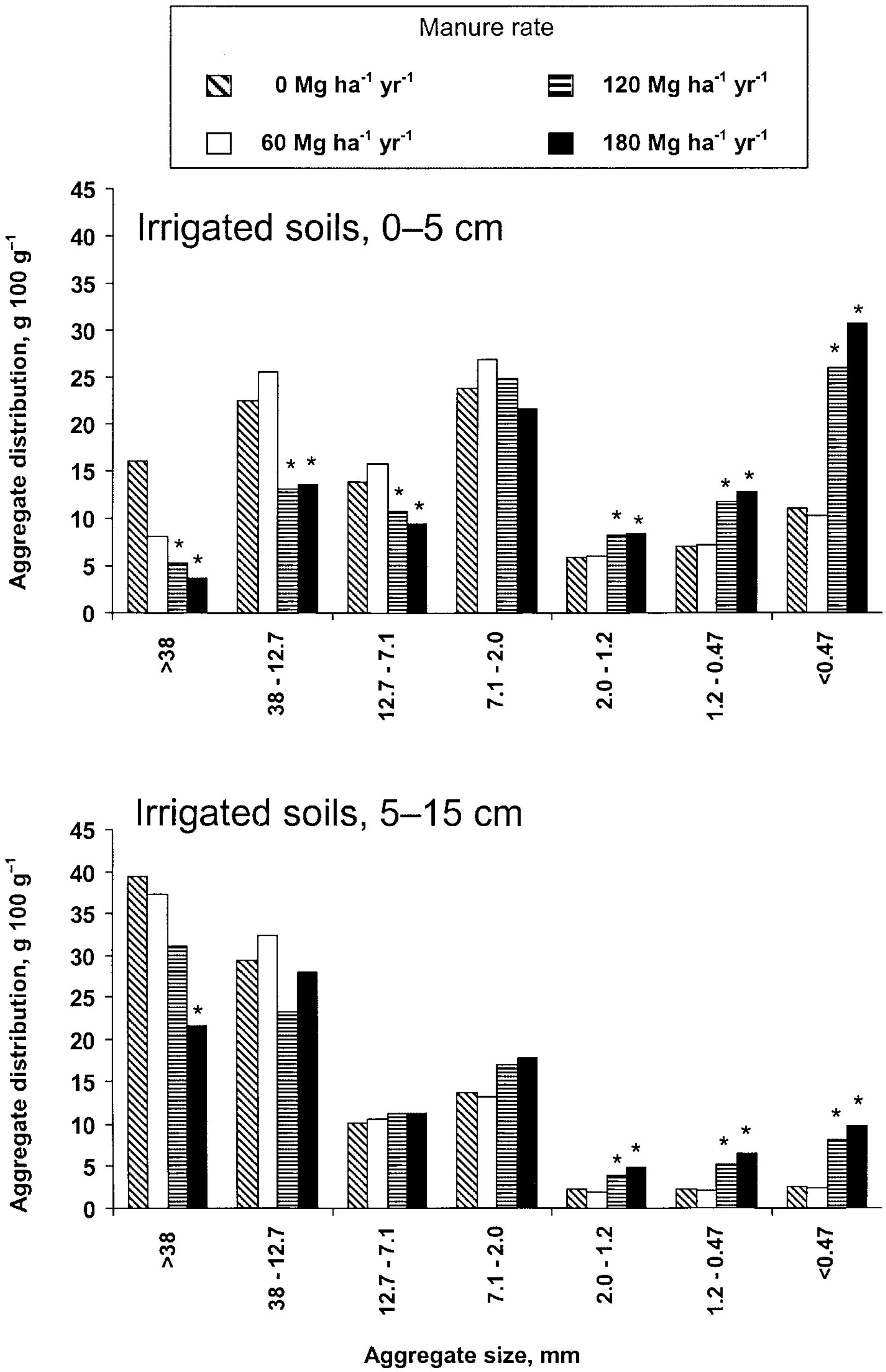

Fig. 2. Aggregate size distribution in the 0- to 5-cm layer and the 5- to 15-cm layer of irrigated plots. Bars with asterisks denote an aggregate distribution that was significantly different ($P < 0.05$, LSD) from unamended plots (0 Mg manure ha^{-1} yr^{-1}).

The presence of more dry-sieved aggregates <2 mm and fewer large dry-sieved aggregates in dryland (>12.1 mm) and irrigated (>7.1 mm) soils that received long-term annual manure applications was unexpected. The application of manure, a source of OM, to agricultural land is generally expected to promote soil aggregation. Manure contains polysaccharides and other aliphatic and aromatic compounds that can bind to soil particles and create organo-mineral complexes important for flocculating aggregates <0.2 μm (Tisdall and Oades, 1982; Angers and N'Dayegamiye, 1991). In addition, manure is a source of energy and nutrients for soil microorganisms and plant roots that produce extracellular polysaccharides known to flocculate soil mineral into aggregates (Tisdall and Oades, 1982). Animal manure has been shown to increase the size and water stability of soil aggregates (Khaleel et al., 1981; Bhatnagar et al., 1985; Sun et al., 1995; Aoyama et al., 1999; Paré et al., 1999).

There are two possible explanations for the apparent

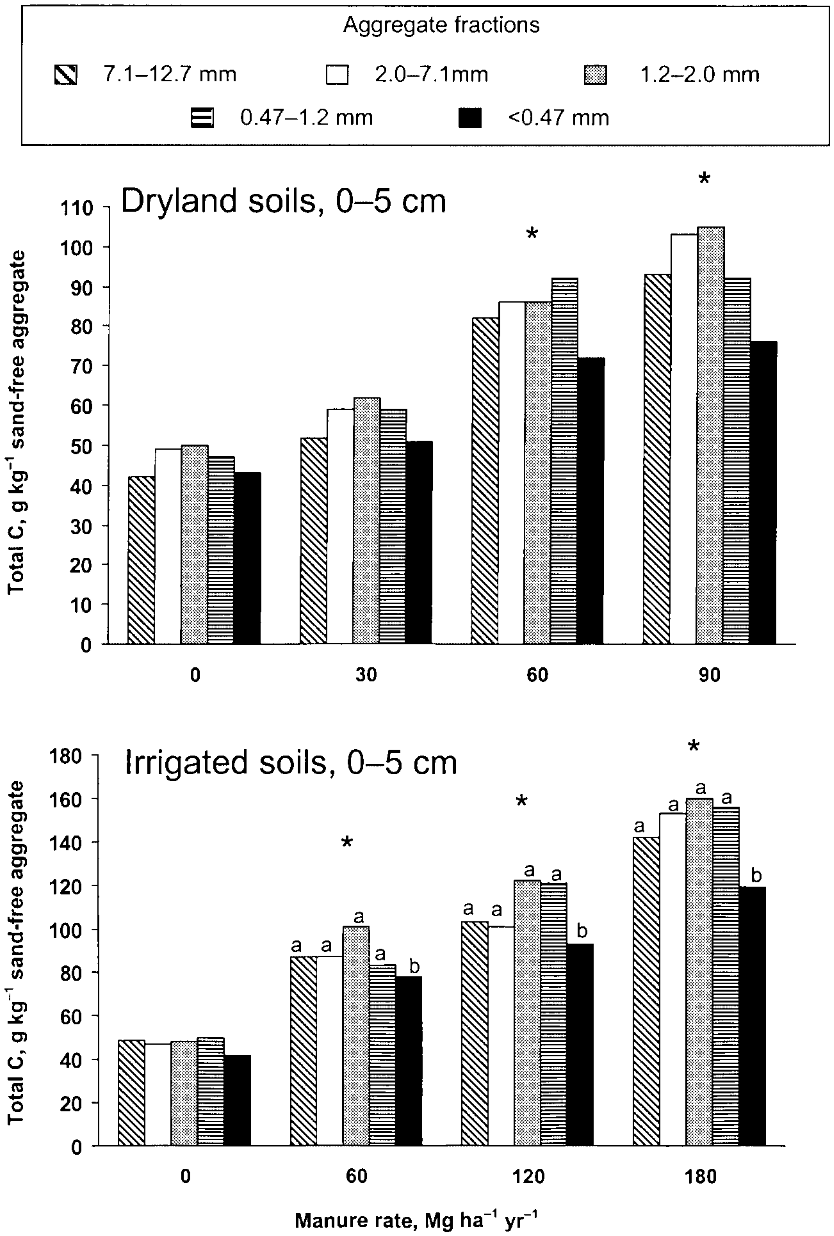

Fig. 3. Total C content of aggregate size fractions in the 0- to 5-cm layer of dryland and irrigated plots. Bars with asterisks denote significant differences ($P < 0.05$, LSD) from unamended plots (0 Mg manure ha^{-1} yr^{-1}). Bars with the same letter, within a manure treatment, are not significantly different ($P < 0.05$, LSD).

dispersion of larger dry-sieved aggregates in the 0- to 5-cm layer of dryland (>12.7 mm) and irrigated (>7.1 mm) soils that received >30 and 60 Mg ha^{-1} yr^{-1} of cattle manure respectively. First, cattle manure contains appreciable quantities of monovalent cations (primarily Na^+ and K^+), NH_4^+, and positively charged organic anions. These compounds are known to promote dispersion of soil colloids (Gillman, 1974; Haynes and Naidu, 1998), and may have contributed to the breakdown of larger (>12.1 and >7.1 mm) soil aggregates in the dryland and irrigated plots, respectively. Salts have accumulated in manure-amended soils under dryland and irrigated conditions, particularly in the 0- to 15-cm soil depth, causing an increase in soluble Na, Ca, and Mg concentrations and displacement of Ca and Mg on the exchange complex by Na (Chang et al., 1991; Miller et al., 1999). Recent measurements of the 0- to 5-cm soil depth at the study site show manure-amended soils have higher electrical conductivity and sodium adsorption ratio values than unamended soils (Table 2). We postulate that the accumulation of Na and displacement of Ca and Mg in soils due to the application of cattle manure has destabilized the 0 to 5 cm of manure-amended soils by dispersing larger soil aggregates.

Second, dry-sieved aggregates in the 0- to 5-cm depth of manure-amended soils may have been dispersed by other substances contained in cattle manure. Appreciable quantities of foreign soil may be mixed with manure when unpaved feedlot pens are scraped with manure loaders, and this soil may promote dispersion of soil

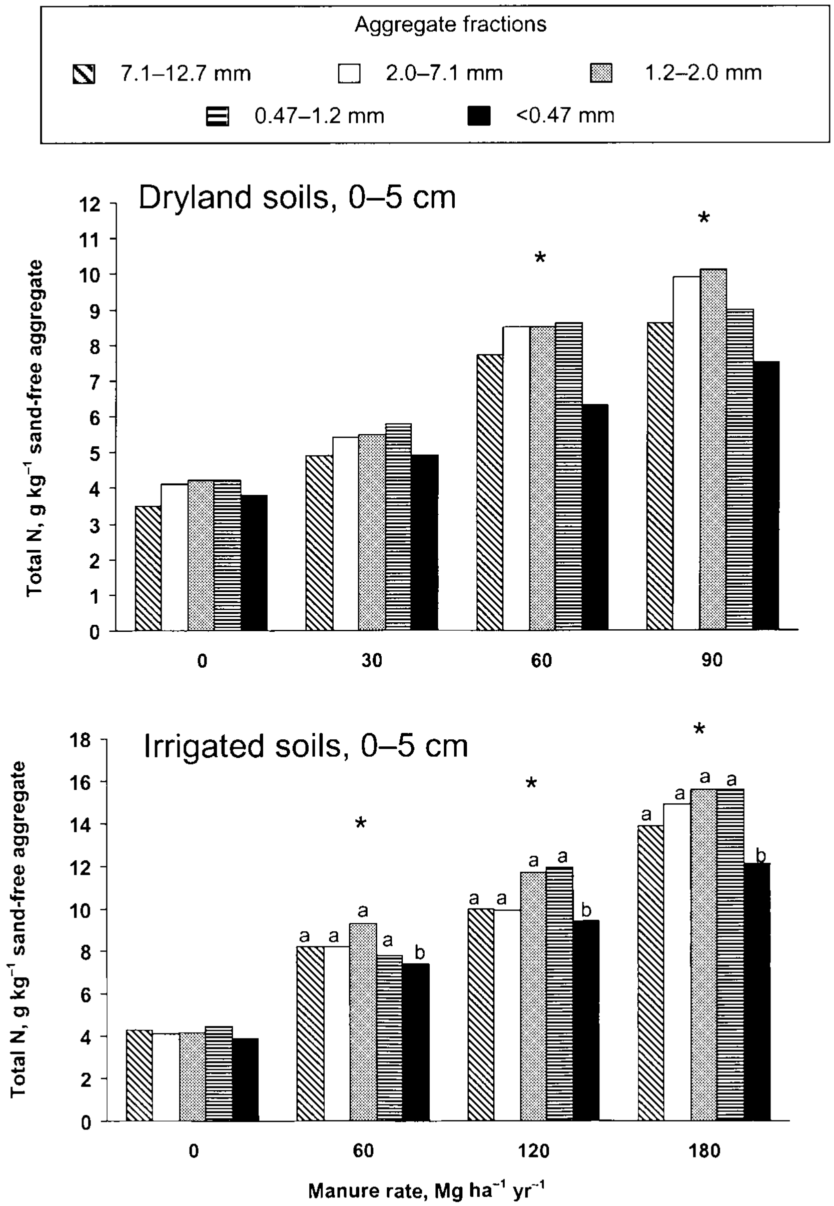

Fig. 4. Total N content of aggregate size fractions in the 0- to 5-cm layer of dryland and irrigated plots. Bars with asterisks denote significant differences ($P < 0.05$, LSD) from unamended plots (0 Mg manure ha^{-1} yr^{-1}). Bars with the same letter, within a manure treatment, are not significantly different ($P < 0.05$, LSD).

colloids. The soil underlying feedlot pens is an important and measurable component of the manure applied at the study site (Gao and Chang, 1996). The soil under the feedlot pens contains 200 g sand kg^{-1}, 350 g silt kg^{-1}, and 450 g clay kg^{-1}, and its repeated application with the manure has led to a significant decline in the sand content in the 0- to 15-cm depth at the study site (Gao and Chang, 1996; Miller et al., 1999). Recent measurements of the 0- to 10-cm soil depth at the study site show manure-amended soils have less sand and more silt than unamended soils (Table 2). Further investigations are required to characterize the foreign soil added to the experimental plots and determine whether the alteration of soil texture following repeated applications of manure may contribute to the dispersion of larger soil aggregates.

We found that dry-sieved aggregate fractions from the 0- to 5-cm depth contained greater quantities of total C, N, and P when soils received 60 Mg ha^{-1} yr^{-1} or more of cattle manure. These results were expected because manure applications increased the organic C, total N, and total P significantly in the top 20 to 30 cm of dryland and irrigated soils (Chang et al., 1991; Chang and Janzen, 1996; Miller et al., 1999; Whalen and Chang, 2001). Greater increases in soil C, N, and P pools have occurred in the irrigated than the dryland plots due to the larger quantities of manure applied to the irrigated plots and more deposition of C in crop residues. Aboveground biomass production is consistently higher in irrigated than dryland plots (Chang et al., 1993; Chang and Janzen, 1996; Whalen and Chang, 2001). It was interesting that some dry-sieved aggregate fractions of

Table 1. Wet-aggregate stability (% water stable, sand-free aggregates) in the 1.2- to 2.0-mm aggregate fraction from dryland and irrigated soils amended with cattle manure for 25 yr.

Water management	Manure rate	Water-stable, sand-free aggregates† Soil depth 0–5 cm	5–15 cm
	$Mg\ ha^{-1}\ yr^{-1}$	%	
Dryland	0	55.8 ± 9.1	69.0 ± 8.8
	30	59.0 ± 6.7	64.4 ± 8.1
	60	70.7 ± 7.9	68.1 ± 6.5
	90	82.4 ± 2.9	74.9 ± 7.2
Irrigated	0	80.0 ± 8.1	81.5 ± 8.2
	60	84.2 ± 5.9	79.8 ± 4.8
	120	84.6 ± 4.2	87.6 ± 4.6
	180	90.8 ± 2.1	86.3 ± 4.2

† Mean ± standard error (n = 6 observations).

manure-amended soils were enriched with total C, N, and P because it suggests certain aggregate fractions, such as the 0.47- to 2.0-mm fraction of irrigated soils receiving 120 and 180 Mg ha^{-1}, are a sink for C, N, and P from manure. If we can identify aggregate fractions where nutrients are preferentially stored, it may be possible to devise management practices that protect and stabilize these fractions.

The enrichment of some aggregate fractions with C, N, and P relative to other fractions does not appear to be consistent with the hierarchical model of aggregate organization (Tisdall and Oades, 1982). According to this model, soil aggregate formation occurs as microaggregates flocculate to form macroaggregates, and hence the largest macroaggregates should contain more OM and nutrients than smaller macroaggregates or microag-

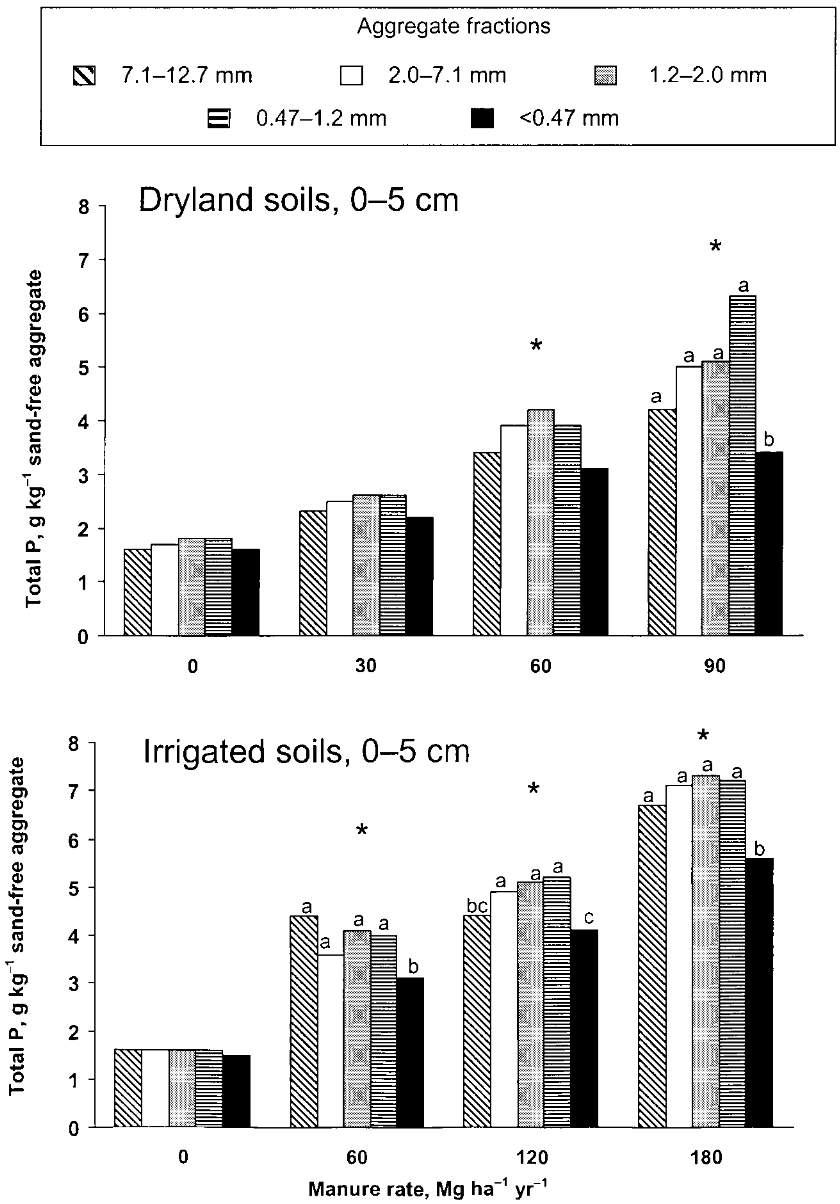

Fig. 5. Total P content of aggregate size fractions in the 0- to 5-cm layer of dryland and irrigated plots. Bars with asterisks denote significant differences ($P < 0.05$, LSD) from unamended plots (0 Mg manure ha^{-1} yr^{-1}). Bars with the same letter, within a manure treatment, are not significantly different ($P < 0.05$, LSD).

gregates. The enrichment of some aggregate fractions with C, N, and P is more consistent with the alternative view of aggregate organization (Oades, 1984; Elliott and Coleman, 1988), which states that after macroaggregates are formed, microaggregates are created and stabilized within the macroaggregates. The breakdown of a macroaggregate by mechanical and chemical agents releases smaller macroaggregates and microaggregates containing undecomposed OM and nutrients from the original macroaggregate (Gale et al., 2000; Six et al., 2000b). Some of the OM and nutrients in the smaller macroaggregates and microaggregates may become increasingly occluded and inaccessible to microorganisms, leading to the stabilization and enrichment of nutrients in these aggregate fractions. The scientific literature contains conflicting reports on nutrient enrichment in soil aggregate fractions following manure applications, and it is not possible to compare our findings with other reports because the methods used to separate aggregate fractions, soil types, agricultural practices, and manure sources differed in every study.

The dry-sieved aggregate fractions between 0.47 and 2.0 mm tended to be enriched with total C and N in irrigated soils receiving manure applications of 120 and 180 Mg ha^{-1} yr^{-1}. Manure-amended soils that received >60 Mg ha^{-1} yr^{-1} had the greatest concentrations of P in the 0.47- to 1.2-mm fraction. The dry-sieved aggregate fraction between 0.47 and 1.2 mm includes the <0.84-mm fraction that has been associated with increased susceptibility to wind erosion in the Canadian semiarid prairies. Therefore, the potential for nutrient transport via wind erosion might be higher in manure-amended than unamended soils, but should be confirmed by measuring the nutrient content of eroded soils from field or wind tunnel experiments. If transported to surface waters, it is possible that more nutrients would be released from aggregates originating from manure-amended than unamended plots. Whalen and Chang (2002) reported a 50% decline in the P sorption capacity of surface (0 to 15 cm) soils from dryland and irrigated plots that received very high manure applications (90 Mg manure ha^{-1} yr^{-1} and 180 Mg manure ha^{-1} yr^{-1}, respectively) for 10 yr. Research is needed to quantify C, N, and P losses from manure-amended soils through wind erosion, and to understand the mechanisms controlling nutrient release from, and sorption to, aggregate fractions of different sizes.

Wet aggregate stability ranged from 55.8 to 82.4% water stable, sand-free aggregates in dryland soils and 79.8 to 90.8% water stable, sand-free aggregates in irrigated soils, and tended to be higher in manure-amended than unamended soils. The stability of aggregates to dissolution and dispersion in water found in this study is similar to or slightly higher than wet aggregate stabilities between 58.0 and 82.9% water stable, sand-free aggregates reported for eroded and stabilized Haploborols (dark brown chernozems) near our study site (Sun et al., 1995). Wet aggregate stability tended to be higher in irrigated than dryland plots, which may be related to the higher soil moisture content in these plots during the growing season. We need to investigate how root production and microbial activity differ in the dryland and irrigated plots to better understand why the proportion of water-stable aggregates between 1.2 and 2.0 mm tends to be higher in the irrigated than dryland plots. Animal manure has been shown to increase the water stability of soil aggregates, and hydrophobic organic compounds such as lipids originating from manure have been proposed as agents that improve wet aggregate stability in manure-amended soils (Bhatnagar et al., 1985; Aoyama et al., 1999; Paré et al., 1999). Although wet aggregate stability tended to increase, there was not significantly greater stabilization of dry-sieved aggregates from the 1.2- to 2.0-mm fraction in cultivated soils that received cattle manure. Future investigations on wet aggregate stability in manure-amended soils should focus on the quantities of binding agents (e.g., hydrophobic SOM compounds) and dispersing agents (e.g., monovalent cations, foreign soil) applied in cattle manure.

CONCLUSIONS

This study showed that long-term manure applications of >30 Mg ha^{-1} to dryland soils and >60 Mg ha^{-1} to irrigated soils can shift the aggregate size distribution from larger (>12.1 mm) to smaller (<2.0 mm) dry-sieved aggregates. Dispersive agents in the manure, namely monovalent cations and foreign soil mixed with the manure, may have caused the shift in aggregate size distribution. Consequently, a greater proportion of the soil mass is at risk of wind erosion following many years of continuous manure applications. We found that dry-sieved aggregate fractions from soils amended with ma-

Table 2. Electrical conductivity (EC) and sodium adsorption ratio (SAR) in the 0- to 5-cm depth, and sand, silt, and clay content in the 0- to 10-cm depth of dryland and irrigated soils after 24 annual applications of cattle manure (adapted from Miller et al., 1999). Values are the arithmetic mean (±SE; $n = 6$ observations).

Water management	Manure rate	EC	SAR	Sand	Silt†	Clay
	Mg ha^{-1} yr^{-1}	dS m^{-1}			g kg^{-1}	
Dryland	0	0.45 ± 0.03	0.24 ± 0.05	270 ± 13	349	381 ± 13
	30	0.72 ± 0.07	0.37 ± 0.09	237 ± 18	380	383 ± 11
	60	0.92 ± 0.06	0.47 ± 0.08	212 ± 10	391	397 ± 7
	90	0.93 ± 0.07	0.46 ± 0.09	188 ± 7	405	407 ± 9
Irrigated	0	0.86 ± 0.07	0.32 ± 0.15	256 ± 13	346	398 ± 5
	60	1.52 ± 0.55	0.52 ± 0.15	189 ± 8	386	425 ± 3
	120	2.12 ± 0.72	0.96 ± 0.21	169 ± 5	400	431 ± 9
	180	3.12 ± 0.58	1.69 ± 0.46	181 ± 7	423	396 ± 10

† Silt content was 1000 − (g sand kg^{-1} + g clay kg^{-1}).

nure rates >30 Mg ha^{-1} yr^{-1} contained more total C, N, and P than unamended soils. The 0.47- to 2.0-mm fraction of dry-sieved aggregates from manure-amended soils, but not unamended soils, tended to be enriched with total C, N, and P relative to other aggregate fractions. Further investigation is needed to determine the mechanisms of aggregate formation in manure-amended soils to better explain why certain aggregate fractions contain higher concentrations of nutrients than other fractions. Wet aggregate stability tended to be greater in irrigated than dryland plots, but cattle manure applications did not stabilize dry-sieved aggregates from the 1.2- to 2.0-mm fraction significantly. Our results indicate that long-term manure applications increase macroaggregate dispersion, which could increase the risk of soil and nutrient loss through wind erosion.

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