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Whey utilization in furrow irrigation: Effects on aggregate stability and erosion

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ABSTRACT

Improving soil structure often reduces furrow erosion and maintains adequate infiltration. Cottage cheese whey, the liquid byproduct from cottage cheese manufacture, was utilized to stabilize soil aggregates and reduce sediment losses from furrow irrigation. We applied either 2.4 or 1.9 L of whey per meter of furrow (3.15 or 2.49 L m^{-2}, respectively) by gravity flow without incorporation to two fields of Portneuf silt loam (Durinodic Xeric Haplocalcid) near Kimberly, ID. Furrows were irrigated with water beginning four days later. We measured sediment losses with furrow flumes during each irrigation and measured aggregate stability by wet sieving about 10 days after the last irrigation. Overall, whey significantly increased aggregate stability 25% at the 0–15 mm depth and 14% at 15–30 mm, compared to controls. On average, whey reduced sediment losses by 75% from furrows sloped at 2.4%. Whey increased the aggregate stability of structurally degraded calcareous soil in irrigation furrows.

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1. Introduction

Cheese whey is the liquid byproduct of cheese manufacture. In the US, nearly 44×10^6 Mg of whey are produced annually in the manufacture of hard and cottage cheeses (National Agricultural Statistics Service, 2007). While whey varies in character depending upon cheese production process, it is generally a mild acid with high soluble salt, chemical oxygen demand (COD), and fertilizer nutrient content, compared to most other waste waters (Robbins and Lehrsch, 1998). Whey is often about 8% solids and commonly contains 40–50 g kg^{-1} of readily decomposable organic compounds, primarily proteins and lactose (Kelling and Peterson, 1981). Some wheys contain more than 1000 mg Na^+ kg^{-1}, limiting their usefulness in agriculture (Robbins and Lehrsch, 1998).

Incorporated low-Na^+ whey improves impaired chemical and physical properties of sodic soils (Robbins and Lehrsch, 1992; Jones et al., 1993b; Lehrsch et al., 1994). Soluble salts in the whey reduce the diffuse double-layer thicknesses of clays, promoting flocculation. Adding and incorporating lactose and whey proteins in soil stimulate aerobic microbes that produce polysaccharides and other organic extracellular compounds and promote fungal growth (Sonnleitner et al., 2003), both of which aid the formation and subsequent stabilization of soil aggregates (Amézketa, 1999; Lynch and Bragg, 1985; Roldán et al., 1996). Soil structural improvements on eroded and/or degraded lands are often necessary during rehabilitation (Logan, 1992). If whey improves the structure of eroded or non-sodic soil, its use as a soil amendment would transform an often discarded byproduct into a valuable resource, providing cheese producers in certain localities another income stream or, in other areas, reduced disposal costs. Since whey is mostly water, its use as a soil amendment is economically feasible only near the whey source if transportation costs are borne solely by the landowner (Zall, 1980; Robbins and Lehrsch, 1998).

Erosion from furrow-irrigated cropland decreases yield potential (Carter, 1993) and degrades surface water quality (Carter, 1990; Lentz et al., 1996). Techniques to control furrow irrigation-induced erosion include vegetated filter strips, mini-basins, residue placement in furrows, and polyacrylamide (PAM) treatment of furrow irrigation water (Brown et al., 1998; Brown and Kemper, 1987; Carter, 1990; Lentz and Sojka, 1994). PAM treatments are particularly effective and widely adopted (Lentz and Sojka, 1994; Sojka et al., 2007).

An alternative or complimentary approach to reducing furrow erosion may be to stabilize aggregates at and below furrow wetted perimeters by applying whey to soil. Kelling and Peterson (1981), studying acid soils in Wisconsin, observed that whey-induced increases in aggregate stability were associated with reduced erosion rates. Bjorneberg et al. (1999), in contrast, in a study of furrow erosion from manure- and whey-treated topsoil and subsoil, noted that soil loss from whey-treated topsoil was among the highest they measured. In their study, however, whey had been applied nearly four years earlier. Since whey is oxidized by soil microbes within a month or two after application (Kelling and Peterson, 1981; Robbins and Lehrsch, 1998), the erosion responses they

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detected were not likely a consequence of the whey applied 46 months earlier.

Brown et al. (1998) reported that whey and small grain straw placed in irrigation furrows effectively decreased irrigation-induced erosion and increased seasonal infiltration. They did not, however, identify the physical processes operating or the mechanisms responsible for reduced erosion from whey-treated furrows. In their study, whey was applied without incorporation to non-sodic soil surfaces prior to irrigation but whey effects on soil structure were not measured. After irrigating, they observed that a surface seal, indicative of soil structural breakdown, had formed along the wetted perimeters of furrows that had not received whey. However, where whey was applied, surface aggregates appeared to be more stable, especially during the first few hours of the first irrigation after whey application. This observation is consistent with previous work showing that soil erodibility and erosion often decrease as aggregate stability increases (Luk, 1979; Kemper et al., 1985; Barthès et al., 2000). In some instances, erodibility and erosion increase with aggregate stability for reasons not yet known (Amézketa, 1999).

Whey is known to increase aggregate stability where it is incorporated into the surface of structurally weak, sodium-affected soils (Robbins and Lehrsch, 1992; Lehrsch et al., 1994). We do not know, however, whey effects on the structure of calcareous but non-sodic soils. Nor do we know whether surface-applied whey must be incorporated for its effects on the structure of such soils to be manifest. Whey effects on calcareous soils need to be further elucidated (Amézketa, 1999; Douglas et al., 2003). We hypothesized that whey applied to furrows of non-sodium-affected soils before they were irrigated would increase the stability of aggregates at and below furrow-wetted perimeters. Stable aggregates along the wetted perimeter would resist slaking and reduce seal formation, thus maintaining acceptable infiltration and aeration (Brown et al., 1988). Greater infiltration would also reduce down-furrow flow rates and hydraulic shear imposed on the wetted perimeter. Both detachment and transport would be minimized, thereby reducing sediment loss rates (Trout and Neibling, 1993; Lehrsch et al., 2005). In this study, we determined whey effects on aggregate stability in and sediment losses from irrigation furrows on two calcareous field sites in 1991.

2. Methods

2.1. Soil and whey properties

The study was conducted on a Portneuf silt loam (coarse silty, mixed, superactive, mesic Durinodic Xeric Haplocalcid) near Kimberly, ID, USA. The Portneuf soil formed in loess and its Ap horizon had a saturated paste pH of 7.7, about 9.3 g organic C kg^{-1}, 220 g clay kg^{-1}, and 560 g silt kg^{-1}. The Portneuf's water content is 0.24 kg kg^{-1} at field capacity and 0.10 kg kg^{-1} at the permanent wilting point (McDole et al., 1974). Portneuf soil structure is relatively unstable (Lehrsch et al., 1991) and the soil is susceptible to furrow erosion (Lehrsch and Brown, 1995). Our cottage cheese whey was the byproduct of adding the equivalent of 3 g H_3PO_4 kg^{-1} of milk to coagulate milk proteins. Each kilogram of whey contained about 1100 mg P, 2000 mg K^+, 960 mg Ca^{2+}, 120 mg Mg^{2+}, and 440 mg Na^+. Though not measured, the whey's total nitrogen content was likely about 1500 mg N kg^{-1} (Robbins and Lehrsch, 1998). The whey had a pH of 3.3, an electrical conductivity (EC) of 5.4 dS m^{-1}, a sodium adsorption ratio (SAR) of 3.5, and a density of 1.01 Mg m^{-3} (Lehrsch et al., 1994). Though representative in most respects, this whey had about 25% less EC, 25% less Na^+, and 65% more K^+ than the cottage and creamed cheese wheys reported by Robbins and Lehrsch (1998).

Table 1
Sequence of field operations

Date	Operation	
	Site A	Site B
24 October 1990		Moldboard plowed[a]
5 April 1991[b]	Moldboard plowed	
8 April 1991	Roller-harrowed[a] twice	Roller-harrowed
6 May 1991	Furrowed, pre-plant irrigated	
13 May 1991	Applied herbicide and fertilizer, roller-harrowed twice, planted maize[c] (*Zea mays* L.), furrowed	Applied herbicide and fertilizer, roller-harrowed twice, planted maize, furrowed
16 May 1991[b]		Irrigated
11 June 1991[b]	Cultivated[a]	Cultivated
14 June 1991	Applied whey	Applied whey
18 June 1991	Irrigated	
25 June 1991		Irrigated
2 July 1991	Irrigated	
8 July 1991		Collected soil samples
9 July 1991	Collected soil samples	

[a] Plow was operated to a depth of 0.18 m; roller-harrow to 60 mm; cultivator to 50 mm.
[b] Date is approximate.
[c] Maize row spacing was 0.76 m.

2.2. Statistical design and analyses

We used a split-plot design with treatments (Whey or Control) as main plots and sampling depths (0–15 or 15–30 mm) as subplots when analyzing aggregate stability. At each site, the treatments were randomized in each complete block but the whey treatment was duplicated in each block. Consequently, the whey treatment was replicated ten times and the control five times, with each replicate being one furrow. The experimental design was a randomized complete block when analyzing erosion rates, assumed to be equal to sediment loss rates and referred to as such hereafter. After ensuring that each response variable's treatments had homogeneous variances, analyses of variance were performed using SAS (SAS Institute Inc., 1999).[1]

2.3. Site preparation, whey application, and irrigation

The major field operations on each site were similar, though not always performed on the same day (Table 1). Furrows were 0.76 m apart. Before whey was applied, soil in every furrow was cultivated with a single, 0.25 m-wide sweep, operated at a depth of 50 mm in soil with water contents commonly ranging from 0.05 to 0.08 kg kg^{-1}, drier than the Portneuf's permanent wilting point. Behind each cultivator sweep, we positioned a weighted furrowing tool that re-formed triangular-shaped furrows about 0.18 m wide at the top and 0.1 m deep. After cultivating all plots, we waited three days for the aggregates to strengthen as the soil dried (Kemper and Rosenau, 1984), then applied whey to the treated plots as described below. Thereafter, with no subsequent tillage, all plots were irrigated with water twice (Site A) or once (Site B) as described below, and subsequently sampled. The control plots were cultivated and irrigated in the same manner as the whey-treated plots but received no whey prior to irrigation.

Site A was at 42°32′55″ N latitude, 114°20′13″ W longitude, and had an elevation of 1184 m. Its furrow slopes faced east and averaged 2.4%. A total of 260 L of whey was applied, at an inflow rate of 150 L min^{-1}, to the head of each 30.4 m-long treated furrow on 14 June. Burlap protected the soil surface where the whey entered

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[1] Manufacturer or trade names are included for the readers' benefit. The USDA-ARS neither endorses nor recommends such products.

each furrow. As the whey flowed by gravity through each furrow, it wet the furrow bottom and sides but was observed to cause little, if any, within-furrow sediment loss, in part due to its viscous, sticky consistency (Brown et al., 1998). Small long-throated, 60° V-notch furrow flumes placed at furrow ends were used to measure outflow (Trout, 1992; Trout and Mackey, 1988). Accounting for furrow outflow, we applied about 2.4 L of whey per meter of furrow, equivalent to an areal application of 3.15 L m^{-2}, or an applied depth of 3 mm. We assumed this application to be relatively equal from inlet to outlet of the monitored furrow section since the high inflow rate minimized infiltration opportunity time differences along the section. When we measured the depth of wetting by excavating the bottom of treated furrows near both the furrow inlet and outlet, we found that the whey had infiltrated to a depth of about 60 mm at both locations. The whey was not incorporated after being applied.

Furrows were irrigated beginning four days after whey application. All irrigations with water lasted 12 h. The irrigation water, withdrawn from the Snake River, commonly has a pH of 8.2, an EC of 0.5 dS m^{-1}, and SAR of 0.65 (Lentz and Sojka, 1994; McDole and Maxwell, 1987). Each furrow's inflow rate, measured by timing the filling of a container of known volume, was 11.4 L min^{-1} for the two 12-h irrigations. Furrow outflow rates were measured *in situ* using the V-notch flumes previously used to measure whey outflow. Sediment loss rates were calculated as the product of outflow rate and outflow sediment concentration, the latter determined using the Imhoff cone method (Sojka et al., 1992). Furrow cross sections were commonly parabolic after one or more irrigations with water. We noticed no differences in shape between treated and untreated furrows.

Site B, about 1.6 km southwest of Site A, was at 42°32′26″ N latitude, 114°21′4″ W longitude, and had an elevation of 1195 m. Its slopes were 1.2% and faced west. Whey was also applied on 14 June to this site. At an inflow rate of 150 L min^{-1}, we applied 260 L to the head of each treated furrow. This whey also infiltrated about 60 mm throughout the monitored 61-m-long furrow. The net whey application was 1.9 L m^{-1} of furrow or 2.49 L m^{-2} areal application (application depth of 2.5 mm). For the subsequent irrigation of Site B with water on 25 June, the inflow rate was 15.1 L min^{-1} for the first 5 h but, owing to low runoff and thus sediment losses, was then increased to 18.9 L min^{-1} for the remaining 7 h of the irrigation. Otherwise, the irrigation of Site B was the same as for Site A.

2.4. Soil sampling and analyses

Soil samples for aggregate stability were collected from Site A seven days after irrigating and from Site B 13 days after irrigating (Table 1). While aggregate stability changes in the first few days after a soil is wetted (e.g., freshly irrigated), stability changes little once surface soil has dried one to two weeks after being irrigated (Blake and Gilman, 1970). Duplicate samples were taken from the bottom of each furrow about 29 m downstream from the furrow head on Site A and about 62 m downstream from the head on Site B. At each sampling location, soil was first excavated to expose a vertical face perpendicular to the furrow's centerline. A spatula was then inserted horizontally about 80 mm into this face, undercutting the 150-mm-wide sample. From each exposed face, a small, approximately 150-g, bulk sample was collected from the soil surface to a depth of 15 mm, and a second bulk sample from 15 to 30 mm. Samples were taken to the laboratory and stored, still field-moist, in air-tight containers at +6 °C until analyzed.

Aggregate stability was measured using the procedure of Nimmo and Perkins (2002), modified by Lehrsch et al. (1991) to use field-moist 1–4-mm aggregates, rather than air-dry 1–2-mm aggregates. We gently dry sieved the moist bulk samples by hand to obtain 1–4-mm aggregates. Those still-moist aggregates, having initial water contents of 0.03–0.17 kg kg^{-1}, were wetted to a water content of 0.30 kg kg^{-1} in 0.5 h with a cool aerosol produced by a non-heating vaporizer (Humidifier Model No. 240, Hankscraft[1], Reedsburg, WI) immediately prior to wet sieving. Aggregate stability was reported as the weight percent of aggregates that remained stable on a 0.25-mm sieve after being sieved in deionized water for 180 s.

3. Results

3.1. Aggregate stability

Whey substantially increased aggregate stability on both sites (Fig. 1). On Site A, compared to controls, whey increased aggregate stability more than 30% at 0–15 mm and by 14% at 15–30 mm. On Site B, aggregate stability increased 18% at 0–15 mm and 14% at 15–30 mm, compared to controls. When averaged across both depths on Site B, aggregate stability after whey treatment was 88% vs. 76% for the control ($LSD_{0.05} = 3.0\%$). Thus, on sites with slopes of 1.2% and 2.4%, whey consistently and significantly increased the stability of aggregates from the soil surface to the 30-mm depth, compared to controls.

Whey caused aggregate stability at 0–15 mm to increase more on Site A than Site B (Fig. 1), likely due to more whey proteins and lactose being applied to Site A than Site B (26% more whey was applied to Site A than B). Though whey increased surface aggregate stability on both sites, the 3.15 L m^{-2} rate applied to Site A was relatively more effective at improving soil structure than the 2.49 L m^{-2} rate applied to Site B. Compared to Site B, Site A had steeper furrows, was more eroded and, when untreated, had fewer stable aggregates (Fig. 1). Where whey was applied to Site A, stability increased to levels comparable to or greater than that of the untreated, less eroded Site B (Fig. 1).

Averaged across sites, aggregate stability of whey-treated furrows was 15% greater (significant at $P < 0.001$) near the surface (at 0–15 mm) than at 15–30 mm. In a study of sodic soils, Lehrsch et al. (1994) also found that increases in aggregate stability due to whey applied to the soil surface, then incorporated, were greatest near the surface. Aggregate stability of the controls varied little with depth at either site (Fig. 1).

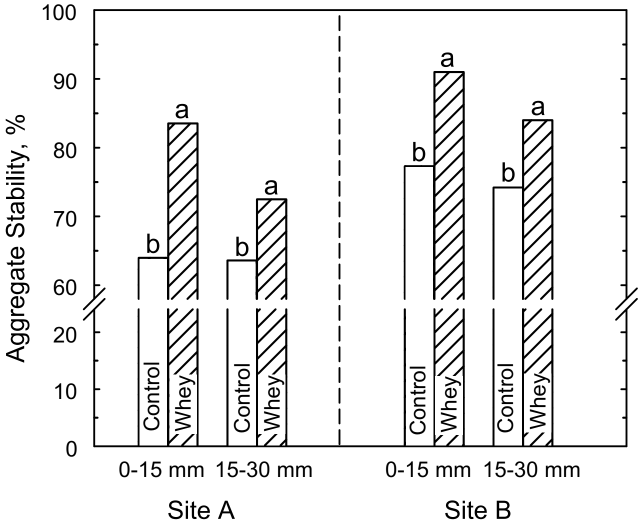

Fig. 1. Whey effects on aggregate stability at 0–15 and 15–30 mm soil depths from Sites A and B. Within soil depths at each site, means without a common letter are significantly different according to a t-test at $P = 0.05$. Site A was irrigated twice and Site B once between whey application and soil sampling.

3.2. Sediment loss

Whey decreased sediment losses from Site A, with whey's effectiveness increasing with time (Fig. 2). Compared to controls, whey reduced sediment losses from the 18 June irrigation by 64%, significant at $P < 0.045$, even though the whey had been applied just four days earlier (Table 1). Though not re-applied, the whey was even more effective on 2 July, 18 days after application. Compared to controls, whey reduced sediment losses by 87% ($P < 0.001$). Whey's potential for decreasing sediment losses apparently was not fully realized with only four days passing between whey application and irrigation.

The sediment losses from Site B were not affected by whey (Fig. 2). Losses from these flatter furrows were uniformly low, regardless of treatment. Where furrows are relatively flat, flow velocities and hydraulic shear are often so low that treatment differences are often less than measurement resolution. When we irrigated this site, infiltration was greater than expected. Consequently, runoff, detachment, and transport were reduced (Lehrsch and Brown, 1995; Trout and Neibling, 1993).

3.3. Association between aggregate stability and sediment loss

We compared sediment loss rates measured from each irrigation with aggregate stability measured on soil samples taken from furrow bottoms about 10 days after the irrigation. The samples were taken from the 0- to 15-mm depth in furrows undisturbed since the irrigation. On Site A, sediment losses decreased linearly with increasing aggregate stability for each of the two irrigations. The relationship was significant for 18 June at $P < 0.065$ (not shown) and for 2 July at $P < 0.001$ (Fig. 3). The correlation between sediment losses on 2 July and aggregate stability was $r = -0.85$. As aggregate stability ranged from 50% to 90%, every 10 percentage point-increase in aggregate stability decreased sediment losses more than 6 Mg ha^{-1} (Fig. 3). On Site B, there was no relationship between aggregate stability and sediment losses (data not shown). Loss rates on Site B were minimal, near measurement resolution and little affected by whey (Fig. 2).

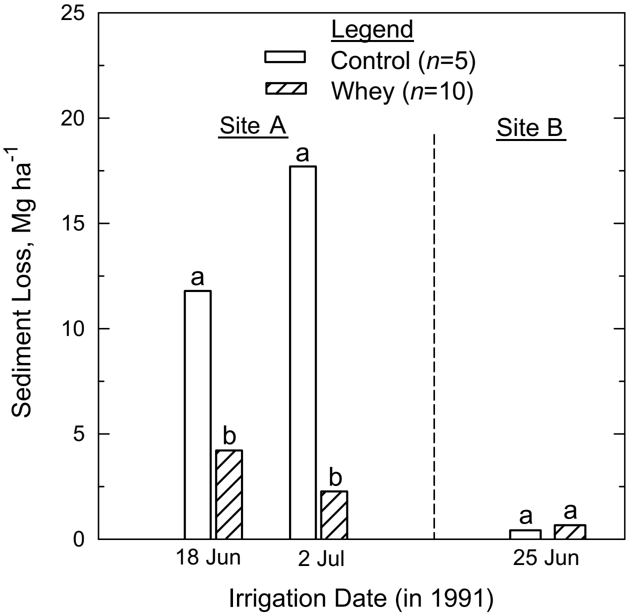

Fig. 2. Whey effects on furrow sediment losses from Sites A and B. Within irrigation dates, means without a common letter are significantly different according to a *t*-test at $P = 0.05$.

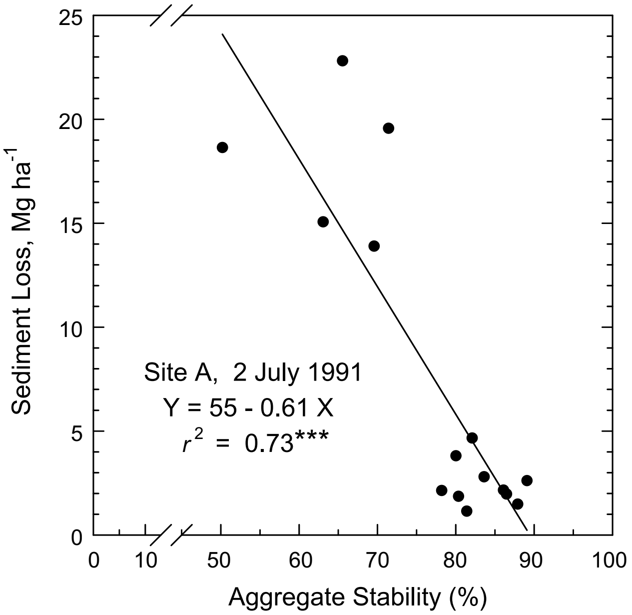

Fig. 3. Effects of aggregate stability, measured at 0–15 mm, on furrow sediment losses from the 2 July irrigation of Portneuf silt loam on Site A.

4. Discussion

Both physical and biological processes were likely responsible for increasing aggregate stability where whey was applied (Fig. 1). Whey soluble salts and phosphoric acid may have flocculated clay to form new aggregates. As noted in the literature, newly formed or existing aggregates can be stabilized by calcium phosphate precipitate, fungal hyphae (Tisdall et al., 1997), and microbial extracellular polysaccharides (Roldán et al., 1996). Polysaccharides can be produced by aerobic microorganisms (Lynch and Bragg, 1985), stimulated by whey's readily oxidizable lactose and milk proteins (Robbins and Lehrsch, 1992; Lehrsch et al., 1994).

Aggregate stability increases caused by whey (Fig. 1) are more important for reducing sediment loss rates on relatively steep (⩾2%) slopes where uncontrolled furrow erosion is often excessive (Brown and Kemper, 1987). Sediment losses from whey-treated 2.4% furrows (Site A) averaged 75% less than those from control furrows (Fig. 2). These substantial decreases in loss rates suggest that one or two whey applications in the first half of the irrigation season may effectively control season-long erosion. Though sediment loss rates vary throughout the irrigation season (Brown et al., 1995; Lehrsch and Brown, 1995), they are often greatest from late June through early July, or after cultivation. Data shown in Fig. 2 indicate that whey may control sediment losses during that time.

The decreasing sediment loss with increasing surface aggregate stability on Portneuf soil (Fig. 3) suggests that more stable aggregates reduce sediment transport. In our study, whey strengthened aggregates at and below treated furrow-wetted perimeters (Fig. 1). These aggregates were less easily fractured, thus minimizing sealing (Brown et al., 1998), sustaining infiltration, and reducing sediment transport.

Sediment losses can be reduced if soil at furrow wetted perimeters can be stabilized sufficiently to resist shear from water flowing in the furrow (Trout and Neibling, 1993) and resist slaking due to air entrapment (Robbins and Lehrsch, 1998). With less sediment (i.e., fewer small aggregates or aggregate fragments) in the furrow stream, surface seals form more slowly, infiltration rates remain larger, runoff rates are smaller, and furrow erosion is reduced (Kemper et al., 1985; Brown et al., 1988). Thus, to help control sediment losses, producers should endeavor to increase the stability of aggregates along furrow wetted perimeters. Whey applied a few weeks before the first irrigation (and/or after any subsequent cultivation) strengthens aggregates (Fig. 1) and often reduces sediment losses (Fig. 2).

Increases in aggregate stability caused by whey, significant even after one or two furrow irrigations (Fig. 1), can help producers manage soil structure under furrow irrigation. Farmers can likely increase the stability of surface soil aggregates by treating furrows with whey and/or straw to decrease furrow erosion on steeper slopes (Brown et al., 1998), improve soil physical properties on structurally degraded areas, increase water distribution uniformity by minimizing surface sealing, and maintain adequate aeration rates. As an added benefit, applying whey also adds N, P, and K (Robbins and Lehrsch, 1998). By applying whey, farmers may improve yields, crop quality, or both.

To improve soil physical properties or control erosion on remote areas, use of whey alone could be impractical because the transportation of unconcentrated whey (mostly water) is costly and cumbersome. In many areas, however, the whey producer pays to have the whey, at times mixed with ice cream wastewater, transported up to 100 km from the whey source. In many cases, the landowner is also paid to accept the whey while simultaneously receiving its benefits.

On a site-specific basis, whey could help reclaim areas with poor soil structure and/or excessive sediment loss rates. To apply whey at 2.4 L m^{-1} to furrows 0.76 m apart, one should apply 31,500 L ha^{-1} (3370 gal $acre^{-1}$). As ancillary benefits, at these whey rates one would also be applying 29–70 kg N ha^{-1}, 9–35 kg P ha^{-1}, and 32–64 kg K ha^{-1}, depending upon the whey type used (Robbins and Lehrsch, 1998). If furrows are disturbed, as by cultivation, whey should be re-applied for continued, effective erosion control (Brown et al., 1998).

If whey is applied to furrows to improve soil structure by increasing aggregate stability, precautions should be taken. Runoff of whey from treated areas into surface waters should be prevented (Kelling and Peterson, 1981) because whey's large oxygen demand (Jones et al., 1993a; Zall, 1980) could cause oxygen deficits in the receiving water bodies. Summer whey applications totaling more than 4×10^5 L ha^{-1} could impair surface soil hydraulic properties. For example, Lehrsch and Robbins (1996) found that both tension infiltration rates and near-surface unsaturated hydraulic conductivities measured at −60 mm of water potential decreased as whey applications exceeded 4×10^5 L ha^{-1}, that is, an applied depth of 40 mm. If a high-sodium whey was land applied, it could harm soil structure if the sodium dispersed the clay along furrow wetted perimeters (Robbins and Lehrsch, 1998). Odors could also arise from whey ponded on the soil surface (Zall, 1980).

In conclusion, whey applied without incorporation to irrigation furrows on two sites with calcareous but non-sodic soil increased aggregate stability from 14% to 30% more than controls in the uppermost 30 mm of soil below wetted perimeters. From steep furrows where sediment losses are often greatest, on average whey reduced sediment losses by 75%, compared to controls. Aggregate stability was correlated ($r = -0.85$, $P < 0.001$) with sediment loss on one site. There, sediment losses decreased by more than 6 Mg ha^{-1} with every 10 percentage point-increase in aggregate stability. Whey, applied to furrows one to three weeks prior to irrigation, significantly improved soil structure. On average, whey increased surface aggregate stability 25%, compared to controls.

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