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Polymer and sprinkler droplet energy effects on sugar beet emergence, soil penetration resistance, and aggregate stability

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Abstract

Polymers in water applied to soil surfaces may increase aggregate stability and reduce aggregate slaking, thus minimizing crusting and increasing sugar beet (*Beta vulgaris* L.) emergence. We studied a cationic organic polymer, Nalcolyte 8102, manufactured by Ondeo Nalco Co., Naperville, IL, USA. The material's active ingredient is a poly diallyldimethyl ammonium chloride (polyDADMAC), a proprietary quaternary polyamine. Surface-applied Nalcolyte 8102 and droplet energy were evaluated in laboratory and field studies for their effects on sugar beet emergence, soil penetration resistance (PR), and aggregate stability of two sprinkler irrigated, crust-prone silt loams in Idaho, U.S.A. In the laboratory, Nalcolyte 8102 at 1.1 Mg active ingredient (a.i.) ha^{-1} was applied in 74,000 L of solution ha^{-1} of wetted area; 5.4 Mg a.i. ha^{-1} was applied in both 50,000 and 105,000 L ha^{-1}; and untreated water at 49,000 L ha^{-1} was applied as a control. These treatments applied a. 7 mm (7 mm^3 mm^{-2}) of a 5% by volume solution, 5 mm of a 37% solution, a. 10 mm of an 18% solution, and a. 5 mm of untreated water, respectively. Later, at three field sites, Nalcolyte 8102 at 0.7 and 1.1 Mg a.i. ha^{-1} were each applied in 74,000 L ha^{-1} of solution (a. 7 mm of a 3 and 5% solution, respectively) by spraying at planting onto two soils, a Durinodic Xeric Haplocalcid and a Xeric Haplodurid, with sugar beet planted to stand. In the laboratory, Nalcolyte 8102 at 1.1 Mg ha^{-1} increased emergence 2.5-fold (32% to 80%) and reduced PR 3.5-fold (1.34 MPa to 0.39 MPa) at 22 days after planting (DAP), compared with controls. In the field, 0.7 and 1.1 Mg ha^{-1} increased emergence 1.2-fold (48.4 to about 58.3%) 50 DAP and increased aggregate stability after treatment 1.4-fold (68% to 97%) one DAP and 1.2-fold (76% to about 89%) 50 DAP, relative to an untreated control that received no water.

Abbreviations: PR–soil penetration resistance; polyDADMAC–poly diallyldimethyl ammonium chloride; a.i.–active ingredient; DAP–days after planting; NA–not applicable; d_{50}–median volumetric drop diameter; ANOVA–analysis of variance; EC_e–electrical conductivity of the saturated paste extract; SAR–sodium adsorption ratio.

Introduction

Soil crusts inhibit seedling emergence for many crops, but particularly for sugar beet because of small seed size and limited metabolic reserves (De Boodt, 1990; Gabriels, 1990). Crusts are often about 3- to 25-mm thick, transient surface layers that are either denser, structurally different, or more cemented than the soil immediately beneath them (Soil Science Society of America, 1997). Crusts can form on soils throughout the

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world but are a particular problem on unstable, fine sandy and loamy soils with little organic matter, especially in arid and semi-arid regions (Awadhwal and Thierstein, 1985). The impact of raindrops or sprinkler droplets begins the crust formation process by fracturing unprotected, freshly wetted surface aggregates and compacting the uppermost soil layers (Yonts and Palm, 2001). If the rainfall or water application rate exceeds the soil infiltration rate, water that does not infiltrate accumulates in surface depressions, causing unstable aggregates to slake and disperse in the ponded water. Detached soil from broken and slaked aggregates is transported by infiltrating water and deposited in surface pores (Awadhwal and Thierstein, 1985; Lehrsch et al., 2005), forming a thin, less permeable surface seal, with a smaller infiltration rate and hydraulic conductivity than the soil beneath it. Drying consolidates the seal which then forms a dense, hard crust. Depending upon the clay type present, cracks may form in the crust, enabling some seedlings to emerge.

Soil crusts delay sugar beet stand establishment, and reduce plant populations (Gabriels, 1990). In some cases, final plant densities can be reduced to the point that replanting is necessary. Soil crusting in south central Idaho causes more than 3600 ha of sugar beet to be replanted annually (L. Kerbs, 1996, personal communication), at a total annual cost of more than $1.3 million. Replanting costs could be substantially reduced in the intermountain region of the U.S. with a management system that would consistently enable at least 65% of seedlings from sown seeds to emerge through crusted soils in fields planted to stand. Field emergence of 65% at a seed spacing of 0.15 m is equivalent to 130 plants per 30.5 m of row. Such a stand in 0.56-m rows produces a near optimum plant population of about 76,300 plants ha^{-1}, sufficient to essentially maximize sugar yield in irrigated regions of the western U.S. (Yonts et al., 2001).

Sugar beet producers often use cultural or management practices to obtain adequate stands and/or to increase seedling emergence through crusted soils (Ahmad, 1991). Some producers overseed, then thin but their costs increase by \$70 ha^{-1} for extra seed and \$80 ha^{-1} for labor to thin. Mechanical thinning with a special implement may cost \$31 ha^{-1} but is less effective with inconsistent spacing between emerged seedlings, common in crusted soil. Secondary tillage can fracture a continuous crust but often significantly reduces stands (Awadhwal and Thierstein, 1985). Growers in sprinkler-irrigated regions worldwide can apply post-plant, pre-emergent irrigations to reduce crust strength (Awadhwal and Thierstein, 1985). Such irrigations increase production costs, magnify the risk of seedling disease caused by, for example, *Pythium spp.* (Franc et al., 2001), and may actually increase crust strength where surface soil structure is destroyed by cumulative sprinkler droplet impact (Tackett and Pearson, 1965). Irrigation systems can be modified, however, to reduce sprinkler droplet kinetic energy, thereby protecting the soil and increasing emergence (Lehrsch et al., 2005; Lehrsch et al., 1996). Surface mulches of crop residue can slow crust formation by dissipating water droplet kinetic energy (Singer and Warrington, 1992) and reducing evaporation but they can cause some planter's seeding depth to be inconsistent and reduce yields due to phytotoxic compounds being released as residue decomposes (Awadhwal and Thierstein, 1985). Surface applications of concentrated sulfuric acid (Johnson and Law, 1967) or phosphoric acid (Robbins et al., 1972) have been used to control or minimize crusting. Though effective, the acids are hazardous to apply and can damage unprotected equipment. Moreover, acids damage roots and alter the availability of elements to plants.

Both natural and synthetic soil anticrustants have been studied for nearly half a century (De Ment et al., 1955). In agriculture, much of the research focused on aggregate breakdown, sealing, and crusting (De Boodt, 1990; Gabriels, 1990). Crusting can often be prevented where selected organic compounds are applied to increase the stability of surface aggregates (De Ment et al., 1955). Soil aggregate stability is a quantitative measure of an aggregate's resistance to force, often exerted by sieving in water. Aggregate stability is usually reported as the percent by weight of aggregates that remain intact after force is applied. Soils with stable surface aggregates are well aerated and resist both crusting and compaction. Chemical amendments that increase aggregate stability or maintain soil structure may keep infiltration rates high (De Boodt, 1990). Decreases in runoff and erosion from plot surfaces sprayed with polyacrylamide (PAM) were likely a consequence of aggregate stability increases that prevented surface seal formation (Ben-Hur, 1994). A polymer's effectiveness in stabilizing aggregates, controlling crusting, or reducing erosion is dependent upon its chemical properties (Lentz et al., 2000). The use of synthetic organic compounds as anticrustants is often hindered by excessive solution viscosity (Lehrsch et al., 1996; Page and Quick, 1979) and high cost, making their use economical only where high-value crops are produced (Gabriels, 1990). A cationic polymer, Nalcolyte[1] 8102 (identified as Nalco 2190 in older literature), mixed with soil appeared to improve seedling vigor and increase emergence of horticultural crops in field demonstrations (Hoyle, 1983). Ahmad (1991) sprayed this same polymer by hand onto silt loam soils in several small experiments in south-central Idaho. He often found that more sugar beet seedlings emerged from treated than untreated surfaces. Hoyle's observations and Ahmad's small-scale studies indicate that low to medium molecular weight, water-soluble, cationic polymers such as Nalcolyte 8102 may effectively control soil crusting.

The long-term goal of our research is to increase sugar beet seedling emergence by applying a cost-effective, chemical anticrustant, managing the soil above planted seed, and/or modifying irrigation systems. The objective of the laboratory and field studies reported here was to determine the effects of the surface-applied synthetic polymer, Nalcolyte 8102, and sprinkler droplet energy on sugar beet seedling emergence, PR, and surface soil aggregate stability of two crust-prone soils.

Materials and methods

Polymer and soil characteristics

The coagulant Nalcolyte 8102, manufactured by Ondeo Nalco Co., Naperville, IL, is a mildly acidic (pH 4.0 to 5.0) aqueous solution with its active ingredient being poly diallyldimethyl ammonium chloride (polyDADMAC), present in solution at 0.27 kg a.i. kg^{-1}. The polyDADMAC is a polyvalent, cationic, low to medium molecular weight (50–250 kg mol^{-1}) organic polymer with the proportion of charged comonomers in the polymer chain (i.e., charge density) ranging from 80 to 100%. The off-white colored, odorless liquid has a density of 1.09 Mg m^{-3} and is completely soluble in water. Nalcolyte 8102, the name assigned to the product by Ondeo Nalco's Water Treatment marketing group, is identical to Nalco 2190, a now inactive product designation assigned to the same product by Ondeo Nalco's Agricultural Products group about 1980. Nalcolyte 8102 currently costs about \$3.75 L^{-1} (whole product) when purchased in bulk. Nalcolyte 8102 is approved for use in potable water treatment.

Field studies were conducted in 1998 and 1999 on two soils at three sites in southern Idaho. Sugar beet was planted into a moist seedbed in early spring per standard grower practice. The soil studied in the laboratory and at Field Sites 1 and 3 was a structurally unstable Portneuf silt loam, a coarse silty, mixed, superactive, mesic Durinodic Xeric Haplocalcid (Lehrsch et al., 1991). The Portneuf's Ap horizon contained about 560 g silt kg^{-1} and 220 g clay kg^{-1} (USDA classification). Its cation exchange capacity was 190 $mmol_c$ kg^{-1}, pH (in a saturated paste) was 7.7, electrical conductivity in a saturated paste extract (EC_e) was 1.1 dS m^{-1}, sodium adsorption ratio (SAR) in a paste extract was 0.87, and organic C content was about 9.3 g kg^{-1}. The soil, with illite as its predominant coarse clay, exhibited little shrinking or swelling (Lentz et al., 1996). The Portneuf's aggregate stability at study initiation was 93% for the laboratory study, 89% at Field Site 1, and 68% at Field Site 3. Stabilities $\geq$ 90% are highly desirable for many low organic matter, western soils. The Portneuf's seedbed bulk density was 1.22 Mg m^{-3} at Field Site 1 and 1.11 Mg m^{-3} at Field Site 3. A Sluka silt loam, coarse silty, mixed, superactive, mesic Xeric Haplodurid, at Field Site 2 had properties similar to the Portneuf. The Sluka soil contained 600 g silt kg^{-1} and 220 g clay kg^{-1}, had an aggregate stability at study initiation of 91% and a seedbed bulk density of 1.09 Mg m^{-3}.

All studies were designed to make it difficult for seedlings to emerge. First, we chose a frequently used but relatively slow germinating cultivar (Hilleshög Mono-Hy[1] 'WS PM-9') that

[1]Trade names are included for the benefit of the reader and do not imply endorsement of the product by the USDA.

emerged poorly through crusted soil (J. Gallian, 1996, personal communication). Second, the Portneuf soil, used for a laboratory study and present at Field Sites 1 and 3, had a crust-prone, silt loam surface (Eghbal et al., 1996). The Portneuf at Site 3 had particularly weak structure, little organic matter, and slow infiltration rates. Third, the sites were irrigated heavily after planting to destroy surface aggregates and form a seal that reduced infiltration and, later, dried to form a crust.

Laboratory study

Several rates of Nalcolyte 8102 (Treatment designations 8102-5, 8102-18, and 8102-37, Table 1) were evaluated for their effects on sugar beet seedling emergence. The 5% (v/v) concentration of Nalcolyte 8102 of Trt. 8102-5 was chosen because it was similar to that noted by Wallace and Wallace (1986) to effectively stabilize soil aggregates. Higher concentrations were included in this exploratory investigation since the Portneuf soil was quite susceptible to structural breakdown, having surface aggregates that fractured readily with only moderate energy input (Lehrsch and Kincaid, 2000). The design was a randomized complete block with four treatments, each replicated four times, Table 1.

Portneuf soil was collected on 24 August 1995 with a shovel to a depth of 0.25 m from a fallowed portion of Site 3 that had been cropped to barley (*Hordeum vulgare* L.) the previous year. Five days later, soil that passed a 4-mm sieve (water content of about 0.08 kg kg^{-1}) was packed by tapping to a dry bulk density of 1.37 Mg m^{-3} to a depth of 90 mm into sixteen 0.15-m-diameter plastic pots. Tap water was then poured onto the soil to raise the soil water content to 0.25 kg kg^{-1} (field capacity; matric potential of −33 kPa). After allowing about 18 h for soil water redistribution, we used a positioning template to place one 'WS PM-9' sugar beet seed, in the form of a clay-covered seed pellet with a diameter of 4.2 mm, in each of 10 positions in a circular pattern on the moist soil in each pot. The seeds were then covered with soil (water content of 0.08 kg kg^{-1}) which was tamped lightly until 19 mm of soil laid above the seeds. The next day, using the positioning template to locate the seeds, we slowly pipetted the appropriate volume (2.5–5.3 ml) of each solution (Table 1) onto a circular, 510-mm^2 area centered above each seed. All seeds in a pot received the same solution. The following day, we formed a seal, that later dried to form a crust, on the pots' soil surfaces by simultaneously sprinkler irrigating the 16 pots on a wooden pallet using two

Table 1. Anticrustant treatments studied in the laboratory and at three field sites in southern Idaho.

Treatment	Nalcolyte 8102[a]		Treatment solution		
	Concentration % (v/v)	Application rate (Mg a.i. ha^{-1})	pH	Volume applied[b] (L ha^{-1} × 10^3)	Equivalent depth (mm)
Laboratory study					
Control: Water[c] (5 mm)	0	0	7.6	49	5
8102-5	5	1.1	7.0	74	7
8102-18	18	5.4	6.2	105	10
8102-37	37	5.4	5.4	50	5
Field studies					
Control	0	0	NA[d]	0	0
Water (7 mm)	0	0	7.6	74	7
8102-3	3	0.7	7.1	74	7
8102-5	5	1.1	6.9	74	7

[a]Product pH was 4.5 and contained 0.27 kg a.i. kg^{-1}.
[b]Liquid applied to wetted area. Actual values equal reported values times the indicated factor.
[c]Water, from the tap, had pH of 7.6, electrical conductivity (EC) of 0.7 dS m^{-1}, SAR of 1.7, and was used to make up all Nalcolyte 8102 solutions.
[d]NA = not applicable.

low-pressure spray heads equipped with smooth deflector plates. The applied water had a droplet size distribution with a median volumetric drop diameter (d_{50}) of 0.9–1.0 mm and low to moderate droplet energy, 5–8 J kg^{-1}, as estimated from Kincaid (1996) and Kincaid et al. (1996). We irrigated the pots on the second, ninth, and fourteenth day after planting (DAP), applying about 11 mm of water each day. Smith et al. (1990) found that simulated rainfall with droplet energy of 8 J kg^{-1} was sufficient to form a surface seal, and subsequently a crust, on untreated soil surfaces. Pots were outdoors when not being irrigated. Air temperatures, on average, reached +25.3 °C during the day and declined to +7.5 °C during the night.

Twenty-two days after planting, we counted the emerged seedlings in each pot and measured soil penetration resistance (Lowery and Morrison, 2002) with a Geotester[1] penetrometer (Model HM-502 Geotester[1], Gilson Co., Inc., Lewis Center, OH). The device was a 130-mm long, hand-operated, direct-reading penetrometer with a 6.0-mm diameter rod, a flat, 6.4-mm tip, and a dial gauge. The gauge pointer indicated unconfined compressive strength in kg of force, sensed by an internal compression spring. We calibrated the device by positioning it vertically and loading it with weights of known mass. Linear regression analysis was used to relate known mass to the force registered by the dial gauge's pointer. To measure PR, we probed vertically downward once in undisturbed soil in seven of the 10 treated areas in each pot to a depth of 6 mm, indicated when a line inscribed on the penetrometer tip was flush with the soil surface. The penetration rate was about 10 mm s^{-1}, though it varied somewhat depending upon field soil conditions. To eliminate variability from one operator to another, in general only one person operated the penetrometer. The maximum force to 6 mm was registered by the gauge pointer and manually recorded. After each measurement, a small button was depressed to reset the gauge pointer to zero. Penetration resistance, expressed in MPa, was calculated by dividing the force by the cross-sectional area of the rod tip. Each pot's PR, as the arithmetic average of all probings within the pot, was analyzed statistically. Since PR is often affected by soil water content (Sojka et al., 2001), we collected soil samples to determine gravimetric water content whenever we measured PR. One composite soil sample of about 45 g was collected to a depth of a. 6 mm from 6 to 8 of the treated areas in each pot. We determined gravimetric water content on a subsample, then stored the remaining still-moist soil in an air-tight container at +6 °C for further analysis.

The aggregate stability of these samples was measured using the procedure of Nimmo and Perkins (2002), modified by Lehrsch et al. (1991). The principal modification was that field-moist 1- to 4-mm aggregates, rather than air-dry 1- to 2-mm aggregates, were aerosol-wetted using a non-heating vaporizer (Humidifier Model No 240, Hankscraft[1], Reedsburg, WI) prior to wet sieving. Aggregate stability was reported as the weight percent of aggregates that remained stable after sieving on a 0.25-mm sieve in distilled water for three min.

Field sites 1 and 2

Site 1, 4 km north of Filer, ID, was cropped to potato (*Solanum tuberosum* L.) in 1997. It was moldboard-plowed to a depth of 0.25 m in late Fall, then roller-harrowed (to 60 mm), and bedded about 20 April 1998 prior to planting. Site 2, 1.6 km west of Filer, ID, was cropped to winter wheat (*Triticum aestivum* L.) in 1998. After wheat harvest, the site was moldboard-plowed, roller-harrowed, land-planed, then bedded in the Fall. A spring-tooth harrow removed the uppermost 50 mm of soil from the bed tops about 12 April 1999 prior to planting.

Other than site location, soil, and pre-plant tillage, experimental protocols were similar. Irrigation water at all sites was from the Snake River and distributed via canals and laterals. The water commonly has pH 8.2, EC of 0.5 dS m^{-1}, and SAR of 0.65 (Lentz and Sojka, 1994). All plots at each site were irrigated after planting with a low pressure center pivot at the cooperator's discretion to establish an acceptable stand. Site 1 was irrigated four times, about every 4 DAP, applying on average 8 (±3) mm (±1 standard error) of water with a d_{50} of 1.2 mm at each irrigation. Site 2 was irrigated twice, about every 4 DAP, applying 6 (±0.1) mm of water with a d_{50} of 1.0 mm each time. The depth of water applied at each irrigation was measured with catch cans. Each irrigation system produced sprinkler droplets with relatively high droplet energies of 15–16 J kg^{-1}, as estimated from Kincaid (1996).

The experimental design at each site was a randomized complete block with eight replicates and four treatments, listed in Table 1. Some field treatments differed from laboratory treatments because findings of the initial lab study were used to adjust the 8102 rates. 'WS PM-9' sugar beet was planted at Site 1 on 22 April 1998 and at Site 2 on 14 April 1999. Seeds were placed 21 mm deep at a 0.15-m spacing into bedded, 0.56-m rows using a four-row, Milton[1] planter, equipped with double-disk openers and rubber press wheels but no drag chains, traveling at 3.64 km h^{-1}. The seed spacing used to calculate percent emergence was measured in the field by excavating seed planted in a similarly tilled border area adjacent to the plots. At planting, we collected seeds dropped from each planter unit to verify that all units were properly adjusted to not damage the pelleted seed. Plots were 2.24 m wide and about 18.6 m long, with the long axis parallel to the irrigation system lateral. A diversion ditch was created at the upslope plot edge to intercept sediment-laden runoff from upslope.

The solutions were applied using calibrated spray equipment on the planter. Each solution was placed in a 19-L tank pressurized with regulated air to maintain the desired nozzle pressure of about 27.6 kPa. Each solution flowed through approximately 2.3 m of 6-mm (I.D.) hose before reaching two spray nozzles placed in series to supply the solution volume required. We used flat spray-pattern Spraying Systems Co. VeeJet[1] nozzles, one Part Number 8060 and one 8050, to spray each solution in a continuous band onto the soil surface directly above the newly planted sugar beet in each row. The spray was estimated to have a mean drop diameter of 1 mm and droplet energy of 27.6 J kg^{-1}. Each nozzle was turned 45° from the direction of travel to reduce the width of the wetted band and was mounted about 25 mm above the soil behind the planter's rubber press wheels. The nominal band width was 25 mm; actual band width averaged 41 mm. The combined flow from each pair of nozzles averaged 11.5 L min^{-1}.

Soil samples to measure initial aggregate stability were collected within 30 h after planting (but before the first post-plant irrigation) using the sampler of Reginato (1975). We sampled the uppermost 5–6 mm of soil in the plant row from four randomly selected replicates (logistical constraints prevented the sampling of all replicates). At that time, we also used the Geotester penetrometer described above to measure *in situ* PR in four areas of each plot by probing 10 times per plot from the soil surface to 6 mm in undisturbed soil in the plant row in all eight replicates. From those same areas in each plot, a composite soil sample was collected to a depth of a. 6 mm to determine gravimetric water content. Soil samples for aggregate stability and gravimetric water content were collected and PR was measured finally at study's end, about 50 days after planting.

Sugar beet seedlings that emerged from the center 13.7 m of each row were counted beginning about 16 DAP. Emerged plants were counted every 2–4 days during peak emergence, but less frequently thereafter. Plants were counted until nearly mid-June to ensure that all emerged seedlings were recorded. Final emergence was calculated as the ratio of the maximum number of emerged seedlings recorded in any of the last four stand counts to the number of seeds sown, expressed as a percent. The maximum number was used because, in some plots, a few seedlings were lost to sugar beet root maggot (*Tetanops myopaeformis*) after they had emerged and been counted. The studies ended upon reaching our objective, final emergence, and thus were not taken to final yield.

Field site 3

Experimental design, treatments, and irrigation. This study was conducted in 1999 about 2.1 km southwest of Kimberly, ID, on a field fallowed the year before. The design was a split-plot with main plots arranged in randomized complete blocks, with eight replicates. The main plot treatments were two droplet energies, 8 or 16 J kg^{-1} of water, randomly assigned to each 19-m half span of a lateral-move irrigation system (described below). The four subplot treatments are listed in Table 1; each was randomly assigned to one of the four rows under each half span. Plot size and orientation were as at Sites 1 and 2.

Plots were irrigated using a 152-m, four-span lateral-move sprinkler system with low-pressure

(103 kPa nozzle pressure) spray heads positioned 1.8 m above the soil surface and either 1.5 or 2.4 m apart. Spray head nozzle diameters ranged from 4.0 to 5.4 mm, arranged as necessary to equalize the application intensity (about 37 mm h^{-1}) from span to span. The lateral discharge rate was about 7.2 L (min m)$^{-1}$, typical for the middle spans of a center pivot's lateral in southern Idaho. The system was modified to produce droplets that impacted the soil surface with nominal kinetic energies of either 8 or 16 J kg^{-1} (1 J kg^{-1} = 1 J m^{-2} mm^{-1}). Spray heads with typical flat, smooth deflector plates produced the 8-J kg^{-1} energy rate (range 7–9 J kg^{-1}) with d_{50} of 0.7–0.8 mm and spinning, four-groove plates produced the 16-J kg^{-1} rate (range 15–19 J kg^{-1}) with d_{50} of 3.3 mm. In southern Idaho with no wind, droplet energies of 10 J kg^{-1} or more are common for center pivots with single-nozzle, impact-type sprinklers (Kincaid, 1996). The lateral-move irrigation system applied 19 mm of water to the site at 8 and 22 DAP to form a crust on all plots. The depth of water applied at each irrigation was calculated using the lateral's ground speed and discharge rate. During the study, the site received 9 mm of natural rainfall on 1 June.

Tillage and planting. The site was disked (to 0.1 m) in the fall, then roller-harrowed prior to planting. 'WS PM-9' sugar beet was planted 23 mm deep at a 0.16-m spacing into 0.56-m rows using a Milton planter traveling at 3.64 km h^{-1} on 19 May 1999. As part of the planting operation, we formed triangular-shaped furrows 0.18 m wide at the top and 0.1 m deep midway between rows every 0.56 m across the site. Subplot treatments (Table 1) were applied at planting as they were at Sites 1 and 2. A reservoir tillage implement formed 0.22-m deep basins that collected surface water and minimized runoff every 0.76 m in each furrow (Lehrsch et al., 2005).

Soil sampling and statistical analyses. The sampling, analyses, and calculations for aggregate stability, PR, and final emergence were the same as for Field Sites 1 and 2. Data were analyzed with a mixed-model analysis of variance (ANOVA) using SAS (SAS Institute Inc., 1997)[1]. Since field PR data exhibited heterogeneous variances among treatments, we log-transformed that data prior to running the ANOVA. In other instances, we used mixed-model grouping options to account for heterogeneous variances. In the ANOVA for PR, we employed soil gravimetric water content as a covariate to account for water content effects on PR. Residuals from fitted statistical models were confirmed to be normally distributed. Fixed effects were site (that incorporated year effects), anticrustant treatment and, for Site 3 only, droplet energy with their interactions. Response variables were final emergence (hereafter referred to as emergence), PR (as the arithmetic average of all probings in each plot), and aggregate stability, measured at study initiation and conclusion on each site. In general, probabilities ≤ 0.05 were considered significant. Least-squares means were separated using *t*-tests of pairwise differences, with either a Tukey-Kramer or Bonferroni adjustment (Westfall and Young, 1993) to the 0.05 level needed for separation. Where needed, means were back-transformed into original units for presentation.

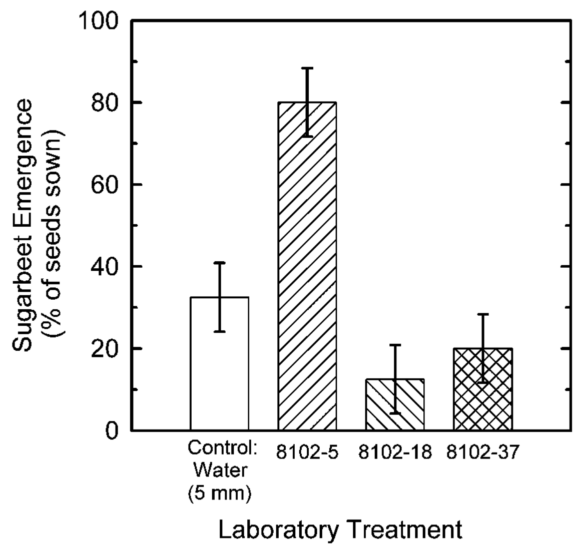

Figure 1. Nalcolyte 8102 effects on sugar beet emergence in Portneuf silt loam in the laboratory after three simulated sprinkler irrigations. The control was untreated tap water applied at a rate of a. 5 mm (5 mm^3 mm^{-2}). Treatment 8102-5 was a 5% by volume solution of Nalcolyte 8102 applied at a. 7 mm, 8102-18 was an 18% solution applied at a. 10 mm, and 8102-37 was a 37% solution applied at 5 mm. Each mean ($n = 4$) is shown ± 1 standard error.

Results and discussion

Laboratory study

Treatment 8102-5 increased sugar beet seedling emergence nearly 2.5-fold more ($p = 0.003$) than the control, Figure 1. In a demonstration in central California, Hoyle (1983) reported 1.7-fold greater emergence of tomato from 8102-treated than untreated soil. His solution, 1.5% Nalcolyte 8102 (v/v, whole product), was less concentrated than our Trt. 8102-5 and he applied about 0.18 Mg a.i. ha^{-1} in about 42,000 L ha^{-1} to a clay loam. Ahmad (1991) studied sugar beet response to 8102 sprayed by hand onto 6-m long, one-row plots in silt loam soils in 9 small field experiments, most in southcentral Idaho. Ahmad (1991) used less solution and smaller 8102 rates (about 0.12 Mg a.i. ha^{-1}) than we used yet still found the polymer to significantly increase sugar beet seedling emergence compared with controls in 6 of 9 experiments. The treatments with more concentrated solution in our study decreased emergence compared to the control, Figure 1. We observed that the 18 and 37% 8102 solutions formed a crust or polymer mat on the soil surface (Entry et al., 2002), possibly by cementing surface aggregates to one another. The less concentrated 5% 8102 solution appeared to stabilize individual aggregates without forming a polymer mat. Though less likely, decreased emergence where we applied more concentrated solutions may also have been due, in part, to the solutions' pH, 5.4 to 6.2, Table 1, or to the product or its constituents being toxic to germinating seedlings. Presence of a crust in Treatments 8102-18 and 8102-37 is supported by their greater PR relative to that of Treatment 8102-5, Table 2, discussed below. McGrady and Cotter (1984) reported that a 10% 8102 (v/v) solution sprayed on the soil surface above chile pepper (*Capsicum annuum* L.) did not increase plant stands relative to controls. These findings suggested that Nalcolyte 8102 may be most effective where applied at 1.1 Mg a.i. ha^{-1} or less, being in solution at concentrations of 5% or less.

Treatment 8102-5 increased emergence by decreasing PR by 71%, relative to controls, Table 2. The relatively low PR for Treatment 8102-5 was not due to differences in soil water content (not shown). The soil water content to 6 mm did not differ ($p > 0.214$) among treatments, being only 0.016 g g^{-1} when averaged across treatments. Treatments 8102-18 and 8102-37 also reduced PR, relative to controls. Treatment 8102-5 also increased aggregate stability compared to controls, Table 2, though the conservative, Bonferroni-adjusted *t*-test did not find the increase significant at $p = 0.05$. A preplanned, single degree of freedom contrast, however, did reveal that the aggregate stability of the 8102-treated plots was greater than controls at $p < 0.004$. Our findings that polymer application decreased PR and increased aggregate stability corroborate observations from a field trial using Nalcolyte 8102 on a Panache clay loam (Typic Torriorthent) (Hoyle, 1983) and measurements from a laboratory study using other polymers on an Arlington soil (Haplic Durixeralf) (Helalia and Letey, 1989). The 8102 concentration in our best laboratory treatment, Trt. 8102-5, was 5% (v/v, whole product), Table 1. Wallace and Wallace (1986) mentioned but did not describe research in which a 4% 8102 (v/v) solution stabilized soil aggregates.

While this study was not designed to elucidate the mechanisms responsible for these improvements in soil physical properties after 8102

Table 2. Anticrustant effects on surface soil penetration resistance and aggregate stability to a depth of 6 mm in Portneuf silt loam in the laboratory after three simulated sprinkler irrigations.

Laboratory treatment	Penetration resistance (MPa)	Aggregate stability (%)
Control: Water (5 mm)	1.34 a[a]	94.3 b
8102-5	0.39 b	95.9 ab
8102-18	0.62 b	97.6 a
8102-37	0.68 b	95.7 ab

[a]Within a column, means followed by a common letter are not significantly different according to *t*-tests of pairwise differences at $p = 0.05$, with a Bonferroni adjustment for the comparisons made.

application, one may nonetheless speculate as to possible modes of action. The positively charged 8102 molecules were likely bound to the negatively charged clay particle surfaces largely through electrostatic attraction. Once bound, they neutralized some particle surface charges, and reduced the repulsive forces acting to separate clay platelets and break aggregates. The adsorbed strands of the polymer molecules also helped to increase both the strength and cohesiveness of individual surface aggregates, enabling them to better resist fracturing from droplet impact. The surface-adsorbed organic cations, being less hydrated than inorganic cations (Uehara and Jones, 1974), also reduced the amount of water associated with clay domain surfaces. Thus, where organic substances were present, re-wetting from rainfall or irrigation caused less swelling between polymer-coated clay domains, and less aggregate disruption. Where aggregates remained stable, relatively large inter-aggregate pores likely remained unobstructed at the soil surface and intact below, allowing water to infiltrate easily and drain readily (Lehrsch and Kincaid, 2000; Uehara and Jones, 1974). Sealing was thus reduced, and crusting, in turn, was minimized. One or more of these processes could explain the greater aggregate stability and less PR after 8102 treatment, Table 2.

Field sites at high droplet energy

The irrigation systems on Field Sites 1 and 2 produced droplets with high energies of 15–16 J kg^{-1}. Data from those sites were combined with half of the data from Field Site 3, that from Site 3's similar high energy treatment, to better test the effects of Nalcolyte 8102 on sugar beet seedling emergence, PR, and aggregate stability under moderate to high droplet energy situations.

Emergence. Nalcolyte 8102 significantly increased emergence, averaged across three field sites, of sugar beet from crusted soils, Figure 2. Compared to controls, Treatment 8102-3 increased emergence 1.22-fold (from 53.6 to 65.5%, significant at $p < 0.001$) while Treatment 8102-5 increased emergence 1.13-fold (from 53.6 to 60.4%, significant at $p < 0.074$). The greater emergence from 8102-treated vs. untreated soil was not due to the 7 mm of water applied with

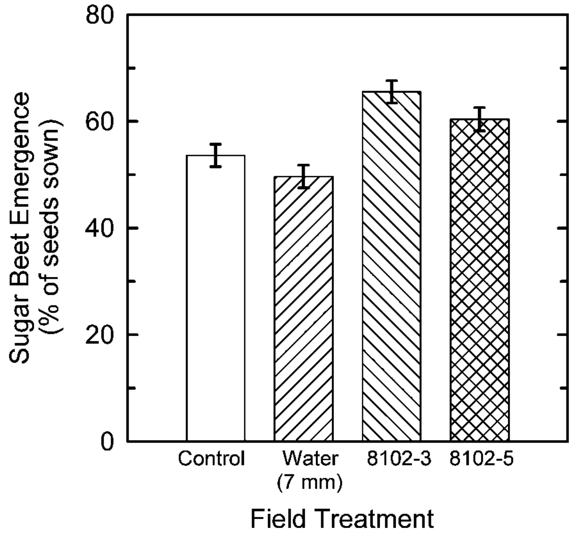

Figure 2. Nalcolyte 8102 effects on field emergence of sugar beet from Portneuf silt loam and Sluka silt loam after being sprinkler irrigated about three times with droplets having kinetic energies of about 16 J kg^{-1}. The Control Treatment was not treated and the Water Treatment was untreated tap water applied at a rate of a. 7 mm (7 mm^3 mm^{-2}). Treatments 8102-3 and 8102-5 were a 3 and 5% by volume solution of Nalcolyte 8102, respectively, each applied at a. 7 mm. Data have been averaged across three sites in southern Idaho. Each mean ($n = 24$) is shown ± 1 standard error.

the Nalcolyte 8102 since the emergence of the Water (7 mm) Treatment was in fact less than that of either the 8102-3 or 8102-5 Treatment, Figure 2. In the field, seedling vigor was visually similar among treatments at all sites. In addition, the interaction between field site and anticrustant treatment was not significant ($p = 0.890$), indicating that the 8102 effects were consistent across years, sites, and soil types. Thus, the 8102 treatment appears to have strong potential for increasing sugar beet seedling emergence from many crust-prone, medium-textured soils in the intermountain region of the western U.S.

At Field Site 2, only about 20 to 30% of the 'WS PM-9' sugar beet seed that were planted emerged from crusted soil immediately surrounding our study area. With such a sparse stand, the cooperator was forced to replant about 16 ha. Emergence was poor in spite of the relatively stable Sluka soil at the site. In contrast, emergence from the 8102-treated portion of Site 2 was about 75% (data not shown). Had the entire 16 ha been treated with Nalcolyte 8102, replanting would likely not have been necessary.

Aggregate stability and penetration resistance. The aggregate stabilizing effects of the anticrustant were more pronounced for soils with weaker structure and soon after application. Relative to controls at study initiation, the 8102 applications increased the stability of the weakest Portneuf soil at Site 3 nearly 1.43-fold (from 67.6 to about 96.7%, Table 3). In contrast, 8102 applications increased the initial aggregate stability of the most stable Sluka soil at Site 2 only 1.08-fold (from 91.4 to about 99%, Table 3), relative to controls. By study's end, only at Site 3 did either of the anticrustant treatments significantly increase aggregate stability more than the controls, Table 3. Fewer differences were detected then because, at Sites 1 and 2, the aggregate stability of 8102-treated soil decreased with time at a faster rate than the controls, in general. Degradation of the surface-applied Nalcolyte 8102 by ultraviolet radiation could have been responsible for the faster decrease in stability with time for treated than untreated aggregates. The trend remained, however, for aggregate stability at each site to be greatest where the anticrustant had been applied.

Relative to controls, Nalcolyte 8102 increased both emergence (Figure 2) and aggregate stability before irrigation for two of three sites (Table 3). Overall, aggregate stability at planting was significantly correlated ($r = +0.54$, $p < 0.001$, $n = 48$) with final emergence. Emergence increased nearly 6% for every 10 percentage-point increase in surface aggregate stability at planting (data not shown). Though the statistical relationship was significant, it explained only 29% of the variation in emergence, indicating that other factors in addition to aggregate stability affected sugar beet emergence.

In contrast to the laboratory study, the anticrustant had little effect on surface soil PR at any field site, due largely to much variability in PR among replicates within treatments. Averaged across all four treatments, the PR for Site 1 was initially 0.40 MPa, though 0.64 MPa by study's end. Similarly, PR for Site 2 was 0.20 MPa, then 0.40 MPa, and for Site 3 was 0.37 MPa, then 0.68 MPa. The anticrustant significantly affected PR only at Site 2 and only initially. In that instance, the PR of treated plots averaged 0.17 MPa, 32% less than the average 0.25 MPa of the control and water only plots. This finding that PR seldom responded to 8102 applications suggests that, in the field, surface aggregate stability may be a better indicator of emergence success than PR. Alternatively, seedling emergence may be more strongly correlated with PR measured using other devices or techniques.

Field site 3 with low and high droplet energy

Emergence. When averaged across droplet energies, the 8102 treatments at Field Site 3 increased emergence by 1.20-fold, relative to controls, Table 4. Emergence was significantly improved by the Nalcolyte 8102, even after two relatively heavy, 19-mm irrigations. Droplet impact from

Table 3. Anticrustant effects on aggregate stability to 6 mm at three field sites in southern Idaho before and after being irrigated about three times with sprinkler systems that produced droplets with kinetic energies of about 16 J kg^{-1}.

Treatment	Site 1[a] Aggregate stability (%)		Site 2[b] Aggregate stability (%)		Site 3[a] Aggregate stability (%)	
	Initial[c]	Final	Initial	Final	Initial	Final
Control	88.9 b[d]	81.7 a	91.4 ab	80.0 ab	67.6 b	79.2 b
Water (7 mm)	75.3 b	86.6 a	78.9 b	71.8 b	54.2 c	67.7 c
8102-3	97.6 a	91.5 a	99.2 a	81.6 ab	96.8 a	86.2 ab
8102-5	98.7 a	89.8 a	98.7 a	81.9 a	96.5 a	92.2 a

[a]The site's soil was Portneuf silt loam.
[b]The site's soil was Sluka silt loam.
[c]Aggregate stability was measured twice, initially on soil samples collected within 30 h after planting but before the first post-plant irrigation, then finally about 50 d after planting.
[d]Within a column, means followed by a common letter are not significantly different according to *t*-tests of pairwise differences at $p = 0.05$, with a Bonferroni adjustment for the comparisons made.

Table 4. Anticrustant effects on seedling emergence and aggregate stability to 6 mm in Portneuf silt loam at Field Site 3 before and after receiving 19 mm of water from each of two sprinkler irrigations.

Anticrustant	Seedling emergence (%)	Aggregate stability (%)	
		Initial[a]	Final
Control	48.4 b[b]	67.6 b	76.4 b
Water (7 mm)	41.7 b	54.2 c	68.1 c
8102-3	58.1 a	96.8 a	87.8 a
8102-5	58.5 a	96.5 a	90.9 a

[a]Aggregate stability was measured twice, initially on soil samples collected within 30 h after planting but before the first post-plant irrigation, then finally about 50 d after planting.
[b]Within a column, means followed by a common letter are not significantly different according to *t*-tests of pairwise differences at $p = 0.061$, with a Tukey–Kramer adjustment (emergence) or a Bonferroni adjustment (aggregate stability) for the comparisons made.
Since sprinkler droplet energy effects were not significant, data have been averaged across droplet energies of 8 and 16 J kg^{-1}.

the two irrigations weakened aggregates and destroyed surface soil structure, forming a crust sufficiently strong to prevent half of the seedlings from emerging from the untreated soil of the controls, Table 4. The Water (7 mm) treatment neither increased emergence nor stabilized aggregates.

The anticrustant treatments increased emergence equally well at both relatively low and high droplet energies (data not shown). Droplet energy as a main effect was not significant ($p = 0.36$) nor was the interaction significant ($p = 0.83$). Thus, 8102 applications appear to be relatively robust and likely effective at increasing sugar beet seedling emergence under many types of pressurized irrigation systems. In earlier research (Lehrsch et al., 1996), sugar beet seedling emergence increased as droplet energy decreased. In this study as well, emergence averaged across anticrustant treatments increased, though not significantly at $p = 0.05$, from 50.1 to 53.3% as droplet energy decreased from 16 to 8 J kg^{-1} (data not shown).

Aggregate stability and penetration resistance. The 8102 applications increased both the initial and final Portneuf aggregate stability, compared to controls, Table 4. Differences in stability between control and treated plots lessened with time because treated aggregates became less stable, possibly due to ultraviolet degradation of the 8102, and untreated aggregates became more stable, as often observed (e.g., Lehrsch and Brown, 1995). Aggregate stability was not affected by droplet energy nor its interaction with anticrustant treatment (data not shown). PR did not respond to treatment, energy, or their interaction (data not shown).

The aggregate stability of the 8102-3 treatment shortly after application was 1.43-fold greater than the control (67.6 to 96.8%, Table 4) and 1.78-fold greater than the water treatment (54.2 to 96.8%, Table 4). Compared to untreated aggregates, the more stable, polymer-treated aggregates were better able to resist slaking and fracturing due to subsequent sprinkler droplet impact (De Ment et al., 1955; Hoyle, 1983). Consequently, sealing and crusting were likely reduced. This would have accounted for the 1.2-fold greater emergence from 8102-treated plots than controls, 48.4 to about 58.3%, Table 4.

Potential benefits. For cost-effective precision agriculture, Nalcolyte 8102 could be applied to soil above newly planted sugar beet in field areas where a producer knew from past experience that crusting would be so severe as to likely require replanting. Judicious targeted application of a 3% Nalcolyte 8102 solution as we did to crust-prone soils in sugar beet-producing areas could increase producer net income by increasing emergence as much as 1.22-fold (Figure 2), easing stand establishment, eliminating replanting, and increasing yields.

Seedling emergence of sugar beet and other small-seeded or horticultural crops can be increased in a cost-effective manner where polymers or other materials are carefully chosen to alleviate specific soil physical problems, and applied under optimum conditions (De Boodt, 1990). Other polymers, anti-crusting agents, new formulations, or application techniques may well prove both effective and economical. Droplet energy minimization alone may increase emergence. As De Boodt (1990) and Awadhwal and Thierstein (1985) concluded, more research is needed. We are continuing to study techniques to increase sugar beet seedling emergence.

Conclusions

Nalcolyte 8102 at 0.7 and 1.1 Mg a.i. ha^{-1} applied to the soil as an anticrustant increased sugar beet seedling emergence. In laboratory and field studies, sugar beet emergence increased from 1.2- to 2.5-fold more than controls where we applied 0.7 to 1.1 Mg Nalcolyte 8102 a.i. ha^{-1} (as a 3 to 5% solution) in 74,000 L of solution ha^{-1} of wetted area to the soil above newly planted seeds. The increased emergence was due to favorable physical conditions on treated soil surfaces. In the laboratory, PR was 3.5-fold smaller and, in both the laboratory and field, aggregate stability was significantly greater on treated than control surfaces.

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