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# Tension Lysimeter Studies of Ion and Moisture Movement In Glacial Till and Coral Atoll Soils[1]

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## ABSTRACT

**The alundum tension lysimeter originally described was modified to allow installation in shallow soils and to facilitate collection of the leachate. The lysimeter plates were located at various depths in two contrasting soil types to study the ion content of the gravitational water. In addition, the influence of potassium (added as KCl) and nitrogen (added as $(NH_4)_2SO_4$) on ion movement in the soil was studied.**

**The ion content of the gravitational water changed markedly with soil type, depth, month of the year, and daily weather conditions. KCl and $(NH_4)_2SO_4$ soil additions distinctly altered established soil dynamics, increasing movement of other soil elements including the radionuclide cesium$^{137}$ from local fallout in 1954 on Rongelap Atoll soils.**

SINCE THE EARLY STUDIES of De LaHire (4) in 1703, and Ebermayer (7) in 1897, lysimeters have been widely used in agriculture and forestry research to obtain information on the nature, amount, and movement of gravitational water. In general, they have been commonly employed to study soil development (12); fertilizer losses (1, 5); and evapotranspiration (8, 10).

The validity of information derived from lysimeters has been repeatedly questioned (3, 11, 15), primarily on the grounds that the soil-air interface at the outlet retards normal soil drainage. Drainage occurs only when the soil immediately above the outlet is saturated; thus, the volume of water flowing from the lysimeter may be less than that which would normally drain from the soil. Most lysimeter types also impose definite restrictions on root development by the very existence of vertical side walls.

These sources of error are particularly significant in studies of ion and water movement through forest soils. Here the investigator is dealing with a community of plants, both annuals and perennials, which have widely developed interrelated root systems.

Thus, to study the influence of various environmental factors on the passage of ions and water through a forest soil, a special type of lysimeter was developed, representing a modification of the tension lysimeter previously reported by the author (2). In order to test the field usefulness of this lysimeter as well as obtain data on movement of water and ions under two widely contrasting environments, the lysimeters were installed in coral atoll soils of the northern Marshall Islands and a glacial till soil of western Washington. The ion content of the gravitational water was studied in relationship to soil type, soil depth, season of the year, daily weather conditions and fertilizer application. The data presented in this article are intended to illustrate the influence of the above factors on the movement and loss of both water and ions in several widely differing soil profiles.

## EXPERIMENTAL PROCEDURE

### The Lysimeter

The lysimeter developed by the senior author (2) minimizes the soil-air interface problem. A negative tension (suction) is placed against the soil through an alundum filter plate. Thus, the capillary force of the soil at field capacity is opposed by the negative tension exerted against the alundum plate. Whenever soil tension is decreased by an increase in soil moisture content, from rain or irrigation, water is removed from the soil until it returns to field capacity. Since the tension against the plate is maintained at a constant value, it is possible an undue amount of water is extracted during the early phases of the drainage cycle. This error would be greatest in heavy soils during intense rain or rapid irrigation. In well-drained soils used in this study, this error was not noticed.

As originally conceived, the tension system was established and maintained by gravity through a water column. The necessary excavation posed practical problems in soils containing hardpan or bedrock; and in other situations, limited the depth at which a lysimeter could be established.

The tension lysimeter as redesigned requires a hole only deep enough to locate the plate. All equipment except the plate is above the ground, simplifying the collection of leachates and servicing of equipment. The components, illustrated in figure 1, are: (*a*) vacuum tank, to maintain the system over an extended period; (*b*) Cartesian manostat, to maintain the desired magnitude of vacuum from the tank to the rest of the system; (*c*) distribution tank, to allow a series of plates to be controlled by a single vacuum tank; (*d*) collection carboy, to receive leachates passing from the lysimeter plates; and lysimeter plate to intercept gravitational water as it passes through the soil. The lysimeter plate is constructed from an 11-inch fused alundum disc as described by Tanner (13) for a tension table and Cole (2) for the original tension lysimeter. All tubing is 3/16-inch ID tygon.

The vacuum tank (figure 2) is constructed from 16-gauge stainless steel reinforced inside with channel iron. A vacuum gauge (*b*) on the side of the tank indicates the vacuum reserve. Air is removed from the tank through the toggle valve

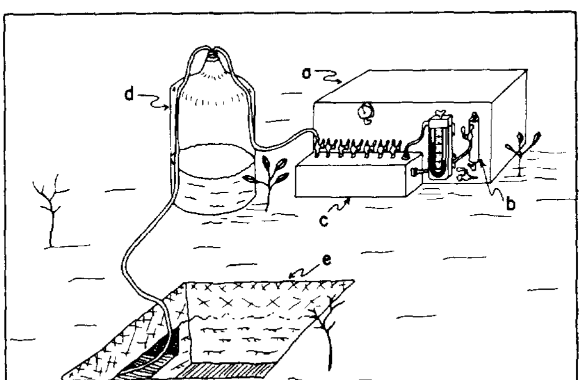


**Figure 1—Alundum tension lysimeter with the tension maintained and controlled through a vacuum system: (a) vacuum tank for maintaining the system over a period of time; (b) Cartesian manostat for controlling the vacuum from the tank to the rest of the system; (c) distribution tank to allow a series of plates installed from one vacuum tank; (d) collection carboy, 5 gallons; (e) hole excavated for installation of plate.**

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(*g*). The Cartesian manostat (*c*) maintains a constant vacuum within the distribution tank (*d*). The magnitude of the distribution tank vacuum is indicated on the U-tube manometer (*e*).

Six plates and associated collection carboys (figure 3) can be simultaneously connected to the distribution tank. Leachate passing into the carboy must first pass through a retaining tube (*e*) which has a volume of 50 ml. Thus, should the vacuum fail, only the leachate in the retaining tube can be siphoned back into the soil. The retaining tube also maintains a constant water level in the carboy and effectively prevents air from entering the tygon tubing (*d*) during short periods of drought. During warm weather a film of transformer oil is maintained on the surface of the leachate to curtail evaporation.

The exact tension placed against the plate is equal to the vacuum within the collecting carboys minus the pressure exerted by the column of water between the carboy and the plate. Consequently, to maintain identical tensions against plates located at various depths and connected to the same distribution tank, the carboys must be placed at equal distances above their respective plates.

## Analysis

Leachates were chemically analyzed in the following manner.

*Nitrogen.*—Nitrogen was determined as the ammonium, nitrate and organic forms.

1. *Ammonium nitrogen.* An aliquot of the leachate was made basic with MgO and distilled into 3% boric acid.
2. *Nitrate nitrogen.* The above aliquot was diluted to 500 ml., 2 g. of Devarda's metal added, and slowly distilled into boric acid. With leachates high in nitrate, it was frequently necessary to redilute the aliquot and continue the distillation for longer periods.
3. *Organic nitrogen.* Organic nitrogen was determined by standard Kjeldal digestion after removing the ammonium nitrogen by distillation as described above.

*Calcium, potassium, phosphorus.*—An aliquot of leachate $>$ 1 liter was evaporated to dryness and treated with 30% $H_2O_2$ until the residue was entirely white. This residue was then redissolved into 10 ml. of 4*N* HCl, heated to 70° C. for 2 hours, diluted to 50 ml., filtered, and then diluted to 100-ml. volume.

1. *Calcium.* A 1- to 5-ml. aliquot of the above solution was titrated with EDTA using murexide indicator.
2. *Phosphorus.* A 25-ml. aliquot was treated with 10 ml. of ammonium vanadate solution and diluted to 50 ml. The intensity of the resulting yellow color was determined at 420 mμ with a Klett-Summerson colorimeter.
3. *Potassium.* The solution was analyzed for potassium with a Beckman Model D. U. flame spectrophotometer at 768 mμ.

*Gamma-emitting radionuclides.*—The remaining leachate was concentrated to $<$ 25 ml. and the gamma-ray spectrum determined with a 3-inch sodium iodide crystal, thallium activated, used in conjunction with a 256-channel analyzer.

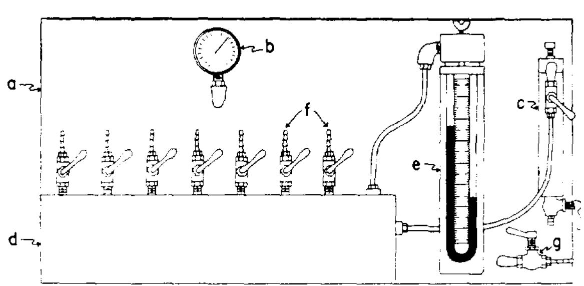


**Figure 2—Vacuum tank: (a) vacuum tank, 16 gauge stainless steel, 2 cu. ft. volume; (b) vacuum gauge for indicating when the tank needs re-evacuating; (c) Cartesian manostat for maintaining a constant vacuum in the distribution tank; (d) distribution tank, 18 gauge stainless steel; (e) V-tube manometer to measure the vacuum in the distribution tank; (f) toggle valves, stainless steel or brass, ⅛-inch pipe threads, to allow a series of plates to be connected to a single tank; (g) toggle valve for evacuating the air.**

## Area

Lysimeters were installed in coral atoll soils at Rongelap Atoll in the northern Marshall Islands and in glacial till soil at Fern Lake in western Washington. In this way, two contrasting soil types were compared.

Parent material of the atoll soils is predominantly foraminiferal sand and coral sand and fragments transported by water and wind to the land areas. Consequently, a recently deposited soil is composed almost entirely of calcium and magnesium carbonate. With the invasion of plant communities and subsequent deposition of organic material, a surface organic horizon develops, changing such soil properties as cation-exchange capacity, field moisture capacity, and the pH.

Mean annual temperature in the Marshall Islands is about 81° F. with little monthly deviation, and a diurnal variation of 10° to 12°. The rainfall occurs primarily between April and November during intense storms which frequently deposit over 1 inch of precipitation. The annual rainfall is about 35 inches with wide annual variations (9).

The soils of Fern Lake originated from a glacial deposit. The climate is moderate with a mean annual temperature of about 50° F. since the area is near sea level, adjacent to Puget Sound. The average annual rainfall of about 46 inches occurs primarily in the winter and spring months (14).

The general soil properties at the various lysimeter areas are summarized as follows:

*Lysimeter area 4, Middle Island coral soil.*—This soil is frequently found in the relatively undisturbed center of the island. Its fertility is exploited by the native population for the cultivation of coconuts. This lysimeter area was located adjacent to a coconut plantation in a *Guettarda-Scaevola* thicket to avoid disturbance by native agricultural practices. The soil surface $A_0$ horizon is 1 to 1½ inches thick underlain by a very dark $A_1$ horizon extending to about 10 inches. Beneath this horizon little organic matter is found and the soil slowly merges into white sand at 40 inches. The soil pH increased from 7.8 at the surface to 9.0 at 40 inches while the exchange capacity decreased from 20 to 1 me. per 100 g. through the same depths.

*Lysimeter area 5, Cordia, Pisonia coral soil.*—This soil is the most fertile in the Rongelap area because of the numerous birds nesting in the *Pisonia* trees. The surface $A_0$ horizon is 1 to 1½ inches thick and heavily matted with roots of *Boerhaavia,* a low succulent ground cover. The $A_1$ horizon extends to 6 inches and is followed by poorly sorted coral fragments containing some organic material. At 24 inches the coral is nearly white. The pH increased from 7.1 at the surface to 8.6 at 20 inches. The cation-exchange capacity decreased from 43 to 2.6 me. per 100 g. through the same depth.

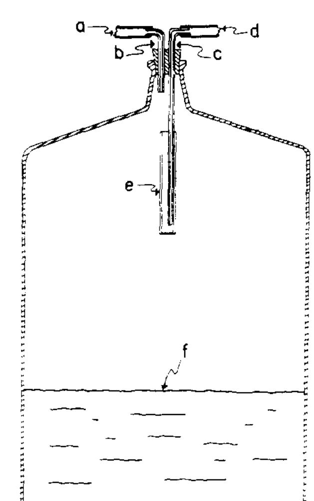


**Figure 3—Leachate collecting carboy for use with the vacuum tank: (a) connection to vacuum tank; (b, c) tenite tubing, ⅛-inch ID, ¼-inch OD; (d) connection to tension plate; (e) retaining tube, tenite, ½-inch ID, ⅝-inch OD, 6 inches long; (f) leachate.**

**Table 1—The influence of soil type on the vertical movement of N, P, K, Ca, $Cs^{137}$ and $Sb^{125}$ through the soil profile. Lysimeter areas 5, 6, and 7.**

| Depth of plates, inches | Precipitation, inches | Precipitation collected as leachate, % | Elements: Nitrogen mg./liter | Nitrogen lb./acre | Phosphorus mg./liter | Phosphorus lb./acre | Potassium mg./liter | Potassium lb./acre | Calcium mg./liter | Calcium lb./acre | Cesium137 count/min./sample | Antimony125 count/min./sample |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Area 5. Cordia, Pisonia coral soil. Rongelap Atoll, Marshall Islands (Aug. 21 - Sept. 18, 1958) | | | | | | | | | |
| 1-1/4* | 12.0 | 83 | 58.8 | 126.1 | 6.6 | 16.1 | 40.0 | 90.1 | 84.3 | 194.3 | 580 | 57 |
| 6 | 12.0 | 56 | 121.6 | 183.5 | 1.8 | 2.8 | 50.5 | 77.6 | 176.1 | 270.6 | 590 | 16 |
| 17* | 12.0 | 45 | 91.6 | 112.8 | 0.5 | 0.6 | 73.8 | 91.0 | 201.5 | 247.7 | 890 | 12 |
| | | | Area 6. Recent deposit coral soil. Rongelap Atoll, Marshall Islands (Aug. 22 - Sept. 18, 1958) | | | | | | | | | |
| 3* | 11.0 | 98 | 0.83 | 2.04 | 0.10 | 0.18 | 0.53 | 1.31 | 26.05 | 63.85 | ** | 63 |
| 18* | 11.0 | 48 | 0.54 | 0.65 | 0.14 | 0.17 | 0.85 | 1.02 | 37.30 | 44.75 | ** | 13 |
| 30 | 11.0 | 14 | 0.29 | 0.15 | 0.17 | 0.09 | 5.80 | 2.92 | 81.40 | 40.50 | ** | 14 |
| | | | Area 7. Glacial till soil (Everett gravelly sandy loam). Fern Lake, Washington (Jan. - July, 1959) | | | | | | | | | |
| 1/2* | 25.35 | 69 | 0.46 | 1.76 | 0.041 | 0.15 | 0.67 | 2.40 | 2.25 | 8.05 | -- | -- |
| 6* | 25.35 | 67 | 0.34 | 1.23 | 0.023 | 0.08 | 0.42 | 1.67 | 1.97 | 7.25 | -- | -- |
| 28* | 25.35 | 35 | 0.37 | 0.71 | 0.031 | 0.06 | 0.28 | 0.37 | 1.82 | 3.35 | -- | -- |

* Average of two plates. ** Not detectable.

**Table 2—The influence of fertilization on the leaching of N, P, K, Ca, and $Cs^{137}$ through the surface humus horizon (1½-inch depth). Lysimeter area 4, Middle Island coral soil.**

| Precipitation, inches | Precipitation collected as leachate, % | Elements: Nitrogen lb./acre | Nitrogen % of control value | Phosphorus lb./acre | Phosphorus % of control value | Potassium lb./acre | Potassium % of control value | Calcium lb./acre | Calcium % of control value | Cesium137 count/min./sample | Cesium137 % of control value |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Control -- no fertilizer additions | | | | | | | | | |
| 12.6 | 73 | 14.8 | 100 | 0.8 | 100 | 6.3 | 100 | 88.8 | 100 | 53 | 100 |
| | | 200 lb./acre of potassium as KCl | | | | | | | | | |
| 12.6 | 99 | 19.9 | 134 | 2.8 | 350 | 205.0 | K addition | 185.4 | 209 | 210 | 400 |
| | | 200 lb./acre of nitrogen as $(NH_4)_2SO_4$ | | | | | | | | | |
| 12.6 | 76 | 196.1 | N addition | 1.0 | 125 | 27.8 | 441 | 444.0 | 500 | 320 | 600 |

*Lysimeter area 6, Recent deposit coral soil.*—This soil has yet to develop a profile except for a cemented layer at 48 inches. The only vegetation, except for scattered *Guettarda* and *Scaevola* bushes, is a surface crust of algae. The pH ranges from 8.9 at the surface to 9.2 at 30 inches. Other than the small cation-exchange capacity of the surface algae, there are essentially no exchange sites in the profile.

*Lysimeter area 7, Everett gravelly sandy loam.*—The soil of this area is very infertile (Douglas-fir site class low V). A dense stand of 30-year-old Douglas-fir is the dominant vegetative cover. The pH through the soil profile remains about 5.3, while the cation-exchange capacity decreases from 11.8 me. per 100 g. at the surface to 4.6 at 24 inches.

*Fertilization areas.*—Three lysimeter areas were established in the coral soil of Rongelap to study the influence of fertilization on ion movement through a 1½-inch surface $A_0$ horizon. Two separate treatments together with an unfertilized control were established at each of the three areas. Nitrogen and potassium were added at the rate of 200 pounds per acre as $(NH_4)_2SO_4$ and KCl.

## RESULTS AND DISCUSSION

### Soil Type and Soil Depth

The interrelationship between soil type, soil depth and the volume and ion content of gravitational water is presented in table 1.

The percentage of precipitation reaching the lower horizons of the soil profiles is markedly decreased by evaporation and utilization by the plant communities. Due to differences in interception by the overstory canopy, differences were found between leachate volumes from plates located at similar depths. At lysimeter area 6, essentially barren of any overstory vegetation, nearly all of the precipitation was accounted for at the 3-inch depth. At lysimeter area 7, interception by the dense canopy of young Douglas-fir removed about 30% of the precipitation.

The movement of nitrogen decreased with soil depth in the areas examined. In the basic soils of Rongelap Atoll, with its hot climate, nitrogen was predominantly leached as the nitrate, while in the acid soils of Fern Lake, with its cool climate, the leachates were chiefly in the ammonium form. The relatively large amounts of nitrogen in the leachates from the *Cordia, Pisonia* soil (lysimeter area 5), were largely due to droppings from nesting birds.

Calcium readily leached through all the soils examined, especially the coral soils of Rongelap, since the soil skeleton in this area is mainly calcium and magnesium carbonate. The leaching of calcium was further enhanced at lysimeter area 5 because of a lower pH caused by leaf litter and bird droppings. The calcium concentration in leachate from the glacial till (lysimeter area 7) remained nearly constant with depth though the total amount decreased, indicating some clay adsorption and plant utilization.

Potassium passed rapidly through the coral soil, the prevalence of soluble calcium and magnesium carbonates apparently giving it little opportunity to remain on the exchange. However, leaching of potassium in the glacial till (lysimeter area 7) was limited by the adsorption and fixation on the clay particles in the soil.

In both the glacial till and coral atoll soils only a small amount of phosphorus moved through the profile, although the addition to the surface (as either litter or bird droppings) was often considerable. This restricted leaching was probably caused by a calcium phosphate precipitation in the coral soil and an iron or aluminum phosphate precipitation in the glacial till soil.

Leachates from the Rongelap soils were analyzed also for gamma-emitting radionuclides originating from radioactive fallout in March 1954 (6). $Ru^{106}$-$Rh^{106}$, $Sb^{125}$, $Cs^{137}$, $Ce^{144}$-$Pr^{144}$, and $Eu^{155}$ were detected. However, reliable quantitative estimates could be made only for $Cs^{137}$ and $Sb^{125}$. It is interesting that $Cs^{137}$ and $Sb^{125}$ were present in leachates collected at depths where the soil contained no measurable radioactivity above background. The patterns of leaching of potassium and $Cs^{137}$ were closely parallel (tables 1 and 2). The *Cordia, Pisonia* soil (lysimeter area 5), with a surface horizon high in organic matter, allowed passage of cesium. In contrast the "recent deposit" soil (lysimeter area 6), virtually free of organic matter, passed antimony but stopped cesium. Total radioactivity in the two soils was 11,000 and 13,000 disintegrations per min. per g., respectively, of which more than 75% was in the top 1 inch of soil.

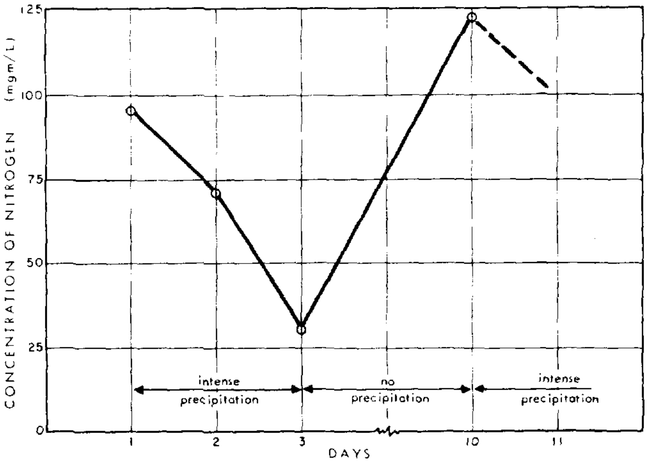


**Figure 4—The variation in concentration of nitrogen in leachates collected beneath the surface organic layer (1½-inch depth) during a 10-day wet and dry weather sequence. Lysimeter area 5, *Cordia, Pisonia* coral soil.**

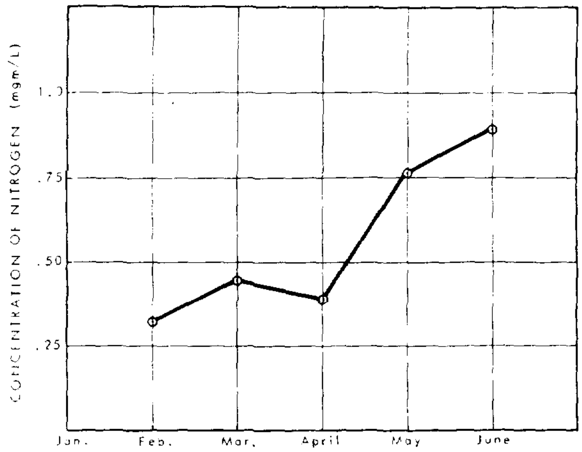


**Figure 5—The variation in concentration of nitrogen in leachates collected beneath the surface organic layer (1-inch depth) from January to June. Lysimeter area 7, glacial till soil (Everett gravelly sandy loam).**

### Fertilization

Data from all fertilized lysimeter areas were similar. Therefore, only results from the "middle island" soil (lysimeter area 4) are presented (table 2).

All or nearly all of the added fertilizer could be accounted for in the analysis of the leachate. It was found that fertilization stimulated leaching of other ions. Potassium, acting essentially as a mass ion, increased the removal of all elements considered in the analysis including the radionuclide $Cs^{137}$. The nitrogen fertilization had an even more pronounced leaching effect since it acted as both a mass ion and a source of $H^+$ ions. Leaching of Ca increased 400% over the control, K 341% and $Cs^{137}$, 500%.

Although the nitrogen was added as $NH_4^+$ ion, it was rapidly converted to the $NO_3^+$ form. Data from lysimeter area 4 demonstrate this conversion (table 3). Pronounced fungal and algal growth in the leachate prevented delineation of the shift in nitrogen form in subsequent collection.

### Precipitation and Temperature

The sequence of precipitation and dry periods had a pronounced effect on the chemical nature of the gravitational water. This is exemplified by the movement of nitrogen through the surface soil at lysimeter area 5 (figure 4). The concentration of nitrogen in the leachate markedly decreased from 90 mg. per liter to 28 mg. per liter after 3 days of intense precipitation. The first leachate collected after 7 days with no precipitation once again showed a high nitrogen concentration. This change in ion concentration caused by duration and intensity of precipitation was not detectable at the 18-inch depth.

The nitrogen concentration in the glacial till leachate of lysimeter area 7 was found to change with season of year (figure 5). This change probably resulted from an increase in soil temperature, increase in moisture utilization by the plants, and a decrease in rainfall. Nitrogen and phosphorus appear to be affected more by seasonal weather changes than other ions examined.

**Table 3—The conversion of nitrogen from $NH_4^+$ to $NO_3^-$ as determined from leachates collected beneath the surface organic layer (1½-inch depth) during the first 10 days after fertilization with 200 pounds per acre of nitrogen as $(NH_4)_2SO_4$. Lysimeter area 4, Middle Island coral soil.**

| Date | N as $NH_4^+$ | | N as $NO_3^-$ | |
|---|---|---|---|---|
| | lb./acre | % | lb./acre | % |
| August 23 | 103.7 | 91 | 9.8 | 9 |
| August 24 | 12.4 | 93 | 1.0 | 7 |
| September 2 | 17.4 | 47 | 19.4 | 53 |

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