Evaluation of the Role of Elemental Sulfur and Sulfate in the Integrated Management of Root Maggots in Canola

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Principal Investigator: Lloyd Dosdall
Alberta Research Council
Postal Bag 4000
Vegreville, Alberta T9C 1T4

Co-applicant: Michael Dolinski
Alberta Agriculture, Food and Rural Development
J.G. O'Donoghue Building
7000 – 113 Street
Edmonton, Alberta T6H 5T6

Summary

Infestations of root maggots (*Delia* spp.) (Diptera: Anthomyiidae) were assessed for Polish (*Brassica rapa* cv. Reward) canola subjected to either drilled or top-dressed applications of ammonium sulfate (at 0, 10, 25, 40, and 50 pounds per acre), powdered elemental sulfur (at 0, 10, 25, 50, and 100 pounds per acre), and prills of elemental sulfur (MF 101® at 0, 10, 25, 50, and 100 pounds per acre). Powdered elemental sulfur was also tested in a spray formulation (at 0, 10, 25, 50, and 100 pounds per acre). The study was conducted during the 1997 and 1998 field seasons near Fort Saskatchewan in a zero-till regimes and near Wostok (1997) and Andrew (1998) in conventional-till regimes.

Two indices were used to assess degree of root maggot infestation: egg-laying by females throughout the season and root damage at the end of the season. In addition, plots were harvested to determine whether seed yield varied among plots subjected to the different treatment types.

This study determined that application method of sulfur/sulfate has importance for the integrated management of root maggot infestations in canola. At all study sites and in both years of the study, when data for the different treatment types and application rates were pooled, less root damage occurred at the end of the season to plants treated with top-dressed sulfur applications than when the sulfur was drilled in with the seed. Significantly greater seed yields occurred in plots treated with top-dressed applications of elemental sulfur/sulfate than in plots subjected to the drilled treatments at Fort Saskatchewan in 1998 and at the Wostok/Andrew sites in both 1997 and 1998. Elemental sulfur applied in a powder formulation drilled in with the seed, and a prill formulation top-dressed on the soil surface, caused significant reductions in damage to taproots from feeding by root maggot larvae, but these reductions in root damage were not accompanied by increased seed yield. There was no apparent impact of ammonium sulfate and sprays of elemental sulfur on root maggot damage to canola taproots or seed yield. Economic assessments to determine whether improved gross returns were achieved with the use of the sulfur/sulfate products indicated that these relationships were variable: improved gross returns occurred with some products at some sites, but consistent relationships were not found. Nevertheless, previous research has established that sulfur is an essential nutrient in the profitable production of canola, and growers should work to ensure adequate levels of this material in agricultural soils.

Introduction

In central and northern Alberta, infestations by larvae of the cabbage maggot, *Delia radicum* (L.), and the turnip maggot, *Delia floralis* (Fallén), can be the single greatest limiting factor in the production of canola. Yield reductions from root maggot infestations can reach 52% in crops of *Brassica rapa* (Polish canola) and 20% in *Brassica napus* (Argentine canola) (Griffiths 1991). Plant damage occurs when larvae tunnel through the roots during feeding, and yield reductions are exacerbated when larval feeding channels are subsequently invaded by root rot fungi (Griffiths 1986a).

Delia radicum and *D. floralis* normally have one-year life cycles in canola in Alberta (Griffiths 1986a, 1986b). Adults emerge from overwintered puparia in mid-May to mid-July and oviposit at the beginning of internode elongation prior to flowering (Griffiths 1986a). Ovipositing females are solitary and lay eggs singly or in small clusters on the basal areas of the plant or in adjacent soil (McDonald and Sears 1992). Most plant damage occurs when second- and third-instar larvae feed on tissues of the phloem, periderm, and xylem parenchyma (McDonald and Sears 1992).

In recent years, research to develop an integrated management strategy for root maggots in canola has determined that cultural and chemical control practices can reduce infestations by these pests and limit economic losses. Effective management practices for root maggots include: 1) planting *B. napus* rather than *B. rapa* in regions where the growing season is of sufficient duration, and selecting the least susceptible cultivars of these species (Dosdall et al. 1994); 2) increasing the seeding rate or plant density (Dosdall et al. 1995a, 1996); 3) applying an insecticidal seed treatment in conjunction with higher seeding rates (Dosdall et al. 1995b); and 4) increasing row spacing at seeding (Dosdall et al. 1998).

Plant nutrients are important for maintaining plant health and for improving seed yield of canola (Thomas 1990), but in spite of their potential effectiveness for reducing infestations of insect pests or for enhancing the ability of host plants to compensate for pest attack, few previous studies have been undertaken to determine the importance of nutrients like sulfur or sulfate for the integrated management of canola pests. In Alberta, approximately seven million acres of agricultural land are deficient in soil sulfur content (Solberg 1997). The importance of sulfur in the production of canola has long been recognized; however, relatively little is known of the role of sulfur either in its elemental or oxidized forms for managing important insect pests. The objectives of this study were: 1) to determine the effect of different rates of application of sulfur and sulfate on infestations of root maggots in canola; 2) to determine the effectiveness of different formulations of elemental sulfur and sulfate on root maggot infestations; and 3) to determine the importance of sulfur/sulfate application method (whether applied top-dressed on the seed row or drilled in with the seed) on infestations of root maggots in canola.

Methods and Materials

The study was conducted at two sites in central Alberta: near Fort Saskatchewan in the northwestern agricultural region of Alberta and near Wostok (1997) / Andrew (1998) in Alberta's northeastern agricultural region. Soil tests confirmed that both sites were deficient in sulfate. The Fort Saskatchewan site was on land subjected to a zero tillage regime and was seeded to a cereal crop during the previous year; the Wostok/Andrew sites were under conventional tillage and fallow in the year prior to our study. The soil type at both sites was black chernozemic, and was fertilized prior to seeding with nitrogen, phosphorus, and potassium according to the recommendations for canola production.

The experiments were randomized split-plot designs with four replications. Application method of sulfur or sulfate, whether top-dressed on the soil surface of the seed row or drilled in with the seed, was assigned to main plots, and sulfur/sulfate formulation and application rate were assigned to sub-plots. Sub-plots measured 6 by 2 m, and were seeded in early spring of each year with a double disc press drill at a rate of 6 kg per ha. All seed was treated with Vitavax rs® to reduce seedling mortality from phytopathogens and herbivory by flea beetles.

Each treatment plot was seeded to *Brassica rapa* cv. Reward. For the drilled and top-dressed application methods the treatments comprised:

1) Controls, with no elemental sulfur (MF 101® prills) added;
2) Elemental sulfur (MF 101® prills) at 10 pounds per acre;
3) Elemental sulfur (MF 101® prills) at 25 pounds per acre;

4) Elemental sulfur (MF 101® prills) at 50 pounds per acre;

5) Elemental sulfur (MF 101® prills) at 100 pounds per acre;

6) Controls, with no elemental sulfur (powder formulation) added;

7) Elemental sulfur (powder formulation) at 10 pounds per acre;

8) Elemental sulfur (powder formulation) at 25 pounds per acre;

9) Elemental sulfur (powder formulation) at 50 pounds per acre;

10) Elemental sulfur (powder formulation) at 100 pounds per acre;

11) Controls, with no sulfate (granular formulation of ammonium sulfate) added;

12) Sulfate (granular formulation of ammonium sulfate) at 10 pounds per acre;

13) Sulfate (granular formulation of ammonium sulfate) at 25 pounds per acre;

14) Sulfate (granular formulation of ammonium sulfate) at 40 pounds per acre; and

15) Sulfate (granular formulation of ammonium sulfate) at 50 pounds per acre;

For the top-dressed application method only, the treatments comprised:

1) Controls, with no elemental sulfur spray (powder formulation) added;

2) Elemental sulfur spray (powder formulation) at 10 pounds per acre;

3) Elemental sulfur spray (powder formulation) at 25 pounds per acre;

4) Elemental sulfur spray (powder formulation) at 50 pounds per acre;

5) Elemental sulfur spray (powder formulation) at 100 pounds per acre;

The prill formulation of sulfur was MF 101®, a bentonite-sulfur product containing 90% elemental sulfur and produced by Tiger Resources Technology Inc. The powder formulation was 99% elemental sulfur comprised of 35-μ-diameter particles produced by the Alberta Research Council's 'micronization process' where molten elemental sulfur is passed through a small pore in a metal cylinder and then passed into cold water. Once in cold water, the sulfur solidifies to form particles that can be separated by size using centrifugation. The sulfur spray consisted of 5-μ-diameter particles and was produced using the same process. The appropriate amount needed for each treatment plot was weighed, mixed with water, and applied uniformly over each sub-plot using a back-pack sprayer onto plants in the rosette stage. The ammonium sulfate was a standard, commercially available product and was pre-packaged and applied at the time of seeding.

The seed drill used in the study was modified to accommodate method of application of the sulfur products to the study plots, whether drilled in with the seed or top-dressed. A Y-shaped metal tube was constructed and attached onto the plastic tubing leading from the seed box containing the sulfur products. A lever on the outside of the Y-tube was used to control a valve within the tube so that the sulfur materials could be directed either to a plastic delivery tube carrying it into the seed row with the seed, or to a plastic tube carrying it onto the soil surface of the seed row ahead of the packing wheels. Sand was added to the powdered sulfur to help carry it through the seed drill and to clear any sulfur particles from the delivery tube.

Once per week for approximately five weeks, counts were performed of the numbers of root maggot egg numbers laid on each of 25 plants from each of the four replicate treatment/control plots. Plants were examined visually and the numbers of eggs laid at the base, the lower leaf axils, and in the soil in a 1-cm-radius and a 1-cm-depth around the plant stalks were recorded.

Plots were harvested at the end of the season with a Hege® plot combine to determine seed yields per plot. Following harvest, a sample of 25 canola roots was collected randomly from each plot, and the roots were bagged and labeled. The root samples were returned to the laboratory where they were washed and scored for degree of root maggot damage using the semi-quantitative rating scale of Dosdall et al. (1994) where 0 = no root damage, 1 = less than 10% of the root surface with root maggot feeding channels, 2 = 11-25%, 3 = 26-50%, 4 = 51-75%, and 5 = 76-100% of the taproot surface area damaged.

Data on root maggot egg numbers, root damage ratings, and seed yield were transformed logarithmically, $\log_{10}(x + 1)$, to stabilize variances among the means. Data were then subjected to analysis of variance and Student-Newman-Keuls multiple comparisons (SAS Institute Inc. 1990) to determine significance of differences in mean eggs laid per plant, and root damage and seed yield at the end of the season for canola subjected to different sulfur and sulfate application methods and rates of application.

Results

The 1997 and 1998 Field Seasons. After seeding in 1997, precipitation was relatively plentiful at both the Fort Saskatchewan and Wostok study sites, resulting in uniform germination and emergence of canola seedlings. In total, 26.8 and 28.1 cm of precipitation were received between seeding and harvest at the Fort Saskatchewan and Wostok sites, respectively. These levels of soil moisture were conducive to development of significant root maggot infestations.

The 1998 field season was characterized by exceptionally dry moisture conditions until late June. However, significant rainfall occurred in late June, and after that time precipitation at both study sites approximated levels equivalent to 30-year averages. In total, 25.6 and 24.1 cm of rainfall were received at the Fort Saskatchewan and Andrew study sites, respectively, during the growing season. The delay in early-season rainfall appeared to influence root maggot populations more than canola plant vigor. At the beginning of the field season, residual soil moisture levels were reasonably high and they permitted uniform plant establishment and growth. Root maggot populations, however, were considerably lower on all research plots until late June when the onset of normal rainfall prompted comparatively high root maggot infestations.

At Fort Saskatchewan, the soil sulfate levels prior to seeding in the upper 15 cm of soil were 6 and 5 ppm in 1997 and 1998 respectively. In the northeastern study sites (Wostok and Andrew), soil sulfate levels prior to seeding were 4 and 6 ppm in 1997 and 1998, respectively, in the upper 15 cm of soil. Approximately five to seven weeks after seeding, most plants were in full bloom. At this time, plants in the control plots showed evidence of sulfur deficiency, displaying some typical symptoms described by Pouzet (1995), including yellowing of the leaves with interveinal chlorosis, stunted growth, and flowers with small, pale yellow petals. Late in the season pod development was complete, and plots were harvested in late September of 1997 and in late August of 1998.

Egg Data. Data from Fort Saskatchewan for both 1997 and 1998, and from Andrew in 1998, indicated that sulfur/sulfate application method (whether the formulations were applied top-dressed on the soil surface as opposed to drilled into the soil with the seed) had no apparent deterrent effect on root maggot oviposition. No statistically significant differences were observed when plants were subjected to drilled versus top-dressed applications of sulfur or sulfate ($P > 0.05$). However, at Wostok in 1997, significantly more eggs were deposited on plants subjected to drilled applications of sulfur/sulfate than when these treatments were applied on the soil surface ($P < 0.05$).

At Fort Saskatchewan in 1997, no statistically significant differences were observed in mean eggs laid per plant, using the drilled application method, for canola subjected to the powder formulation of elemental sulfur, regardless of the application rate ($P > 0.05$) (Fig. 1). However, significantly more eggs were laid on plants grown using the granular application of ammonium sulfate at 40 pounds per acre than for plants receiving the lower rates or 50 pounds per acre ($P < 0.05$). For plants treated with the prill formulation of elemental sulfur, significantly more root maggot eggs were laid on control plants than those treated with prills at rates of 10, 25, and 100 pounds per acre ($P < 0.05$). Using the top-dressed application method, no statistically significant differences were observed in mean eggs laid per plant for canola subjected to granular ammonium sulfate, or the powder or prill applications of elemental sulfur, regardless of application rate ($P > 0.05$) (Fig. 1). However, significantly more root maggot eggs were laid on control plants than those sprayed with elemental sulfur at rates of 10, 25, 50, and 100 pounds per acre ($P < 0.05$).

At Fort Saskatchewan in 1998, no statistically significant differences in mean numbers of root maggot eggs were observed among the different treatment types or application rates using either the drilled or the top-dressed application methods (Fig. 2).

In 1997 at Wostok, using the drilled application method, no statistically significant differences were observed in mean eggs laid per plant for canola subjected to either powder or prill formulations of elemental sulfur, regardless of the application rate ($P > 0.05$) (Fig. 3). However, for granular applications of ammonium sulfate, significantly more eggs were laid on plants grown using application rates of 40 and 50 pounds per acre than for plants receiving lower rates ($P < 0.05$). Significantly more root maggot eggs were laid on plants treated with 10 pounds per acre of ammonium sulfate than on the untreated controls ($P < 0.05$). Using the top-dressed application method, no statistically significant differences were observed in mean eggs laid per plant for canola subjected to powder or spray applications of elemental sulfur, regardless of application rate ($P > 0.05$) (Fig. 3). Similarly, no statistically significant differences in root maggot oviposition occurred among the various application rates of granular ammonium sulfate ($P > 0.05$). However, significantly more root maggot eggs were laid on plants subjected to treatment with 100 pounds per acre of elemental sulfur in the prill formulation than for plants treated with prills at any of the lower application rates ($P < 0.05$).

At Andrew in 1998, using the drilled application method, no statistically significant differences were observed in mean numbers of root maggot eggs deposited on plants treated with any of the application rates of sulfur powder or sulfur prills ($P > 0.05$) (Fig. 4). However, plants treated with drilled applications of ammonium sulfate at 50 pounds per acre had significantly more eggs per plant than plants receiving any of the other ammonium sulfate treatments ($P < 0.05$) (Fig. 4). No statistically significant differences were observed in mean numbers of root maggot eggs laid per plant among the different treatment types and application rates using the top-dressed application method ($P > 0.05$) (Fig. 4).

Root Damage Data. At Fort Saskatchewan in both 1997 and 1998, when data for all formulations and application rates were pooled and analyzed for differences in application method (drilled or top-dressed), it was found that mean root damage values were significantly lower when the sulfur or sulfate formulations were top-dressed than when drilled in with the seed ($P < 0.05$). This relationship was also evident at Wostok in 1997 and at Andrew in 1998.

At Fort Saskatchewan in 1997, no statistically significant differences were observed in mean root damage ratings using the drilled application method for either ammonium sulfate or elemental sulfur prills at any of the application rates ($P > 0.05$) (Fig. 5). However, canola plants subjected to applications of powdered sulfur at rates of 50 and 100 pounds per acre had significantly less root damage than those of control plants or plants treated with powdered sulfur at 10 or 25 pounds per acre ($P < 0.05$). Root damage to controls and plants treated with powdered sulfur at 10 and 25 pounds per acre did not differ significantly from each other ($P > 0.05$). For plants having top-dressed sulfur or sulfate applications, no statistically significant differences occurred in mean root damage ratings for plants treated with either ammonium sulfate or elemental sulfur spray at any of the application rates ($P > 0.05$) (Fig. 5). However, plants treated with powdered sulfur at 10 and 25 pounds per acre had significantly less root damage than those of control plants or plants treated with powdered sulfur at 50 pounds per acre ($P < 0.05$). Compared with control plants, no statistically significant differences in root damage were observed for plants treated with sulfur prills at 10 and 25 pounds per acre, but plants treated with prills at 50 and 100 pounds per acre had significantly less root damage than those subjected to the lower application rates ($P < 0.05$).

At Fort Saskatchewan in 1998, mean root damage ratings were similar and not significantly different for all drilled applications of granular ammonium sulfate and all the prill applications of elemental sulfur ($P > 0.05$) (Fig. 6). However, root maggot damage was significantly lower for applications of 50 and 100 pounds per acre of powdered elemental sulfur than for powdered sulfur at 0, 10, and 25 pounds per acre ($P < 0.05$). No statistically significant differences were observed among the different treatment types for top-dressed applications of sulfur powder and sulfur spray ($P > 0.05$) (Fig. 6). However, mean root maggot damage ratings were significantly lower for prills of elemental sulfur at application rates of 50 and 100 pounds per acre than for elemental sulfur at rates of 0, 10, and 25 pounds per acre ($P < 0.05$). Plants subjected to top-dressed application of granular ammonium sulfate at 10 pounds per acre had significantly lower root damage than plants subjected to any of the other treatments involving ammonium sulfate ($P < 0.05$).

At Wostok in 1997, using the drilled application method, no statistically significant differences were observed in mean root damage ratings for either ammonium sulfate or elemental sulfur prills at any of the application rates ($P > 0.05$) (Fig. 7). However, canola plants subjected to applications of powdered sulfur at rates of 10 and 100 pounds per acre had significantly less root damage than those of control plants ($P < 0.05$). Plants treated with powdered sulfur at 25 and 50 pounds per acre had less root damage than the controls, but this difference was not significant statistically ($P > 0.05$). For plants having top-dressed sulfur or sulfate applications, no statistically significant differences occurred in mean root damage ratings for any of the formulations or application rates ($P > 0.05$). For all treatments, however, a trend of decreasing root damage was observed with an increase in application rate (Fig. 7).

At Andrew in 1998, no statistically significant differences were observed in mean root damage ratings for plants subjected to the various drilled applications of ammonium sulfate and elemental sulfur powder ($P > 0.05$) (Fig. 8). Plants treated with prills of elemental sulfur at 25 pounds per acre had significantly more root damage than untreated controls. No significant differences occurred in mean root damage to plants treated with top-dressed applications of sulfur prills or sprays of elemental sulfur ($P > 0.05$). Plants treated with ammonium sulfate at 25 and 50 pounds per acre had significantly more root damage than plants treated with ammonium sulfate at 40 pounds per acre ($P < 0.05$), and plants treated with elemental sulfur powder at 100 pounds per acre had significantly more root damage than the untreated controls ($P < 0.05$) (Fig. 8).

Yield Data. In Fort Saskatchewan, when yield data for all sulfur/sulfate formulations and application rates were pooled and analyzed for differences in application method, it was found in 1997 that mean yields per plot did not differ significantly regardless of whether applications were top-dressed or drilled ($P > 0.05$). In 1998, however, significantly greater seed yield occurred in plots treated with top-dressed applications of elemental sulfur/sulfate than in plots subjected to the drilled treatments. At the Wostok/Andrew sites, when yield data for all sulfur/sulfate formulations and application rates were pooled and analyzed for differences in application method, it was found in both 1997 and 1998 that mean yields per plot were significantly greater for top-dressed applications of sulfur/sulfate than for drilled applications ($P < 0.05$).

At all study sites in both 1997 and 1998, no statistically significant differences were observed in mean seed yields per plot, regardless of treatment type, application method, or rate of application ($P > 0.05$) (Figs. 9, 10, 11, 12). At Fort Saskatchewan in both 1997 and 1998, however, a trend of slightly increased yield with an increase in application rate was observed for ammonium sulfate when the drilled application method was used. At Wostok in 1997, a trend of increased yield with an increase in application rate was observed for ammonium sulfate and powdered elemental sulfur when the top-dressed application method was used. At Andrew in 1998, a trend of increased seed yield was observed with an increase in application rate for both drilled and top-dressed applications of prills of elemental sulfur.

Discussion

Crop damage from insect pest attack can be affected by applications of fertilizers through alterations in crop growth or nutritional levels of plant parts (Herzog and Funderburk 1986), and the literature contains several examples of insect pest population dynamics that are influenced by soil nutrient levels. For example, McGarr (1942, 1943) found that enhancement of cotton leaf growth through fertilization rendered the crop more attractive to the cotton aphid, *Aphis gossypii* Glover, and Adkisson (1957, 1958) found that this was also true for the cotton fleahopper, *Pseudatamoscelis seriatus* (Reuter), and the cotton bollworm, *Helicoverpa zea* (Boddie). Funderburk et al. (1991) determined that in soybean plantings, larval populations of velvetbean caterpillars, *Anticarsia gemmatalis* (Hübner), increased at higher levels of phosphate; magnesium level, however, did not affect their population densities.

Sulfur has long been known to provide protection to plants against insect pests and diseases; however, the role of sulfur in pest management has often been restricted to foliar applications. For example, foliar applications of elemental sulfur have a repellent effect on some insect pests and sulfur can act as a contact insecticide (McGovran et al. 1969). There is, however, increasing evidence that soil-applied sulfur also has importance for pest control (MacKenzie 1995). Schnug and Ceynowa (1990) found that light leaf spot disease proliferated much more rapidly in environments deficient in sulfur than when soil sulfur content was adequate. Sulfur is an integral component of glucosinolates in Cruciferae, which play an important role in the defence system of the plant against insects and diseases (Schnug and Ceynowa 1990). As glucosinolate content is positively influenced by increasing supply of sulfur, sulfur fertilization may enhance the production of glucosinolates and improve plant resistance (Walker and Booth 1994; Schnug et al. 1995). However, for insect species specialized to attack cruciferous host plants (like diamondback moth, *Plutella xylostella* (L.), root maggots, *D. radicum* and *D. floralis*, flea beetles, *Phyllotreta cruciferae* (Goeze), etc.), high levels of sulfur may increase glucosinolate levels in plant tissues and so enhance the attractiveness of the host plants to attack by these pests. For example, Gupta and Thorsteinson (1960) reported that depletion of the glucosinolates oxybenzyl isothiocyanate and allyl isothiocyanate by sulfur-deficient plant nutrition reduced the attractiveness of the cruciferous host plants *Sinapis alba* L. and *Brassica nigra* (L.) as oviposition sites for diamondback moth.

Root maggot oviposition data indicate that, in general, canola subjected to granular applications of ammonium sulfate drilled in with the seed tended to be more susceptible to egg laying by root maggot females than plants treated with formulations of elemental sulfur. This was particularly evident at the higher rates of application. The increased susceptibility of plants treated with ammonium sulfate may be an expression of the greater phytotoxic effect of this compound on seedlings when applied at high rates. We observed poorer seedling emergence in plots treated with ammonium sulfate at higher rates of application than at lower rates of application, and the surviving seedlings developed larger basal stems because the overall plant density on those plots was reduced. Previous research has shown that root maggot females prefer plants with larger basal stems for oviposition (Dosdall et al. 1996).

Application method of sulfur/sulfate appears to have some importance for the integrated management of root maggot infestations in canola. At all study sites and in both years of the study, less root damage occurred at the end of the season to plants treated with top-dressed sulfur applications than when the sulfur was drilled in with the seed. Significantly greater seed yields occurred in plots treated with top-dressed applications of elemental sulfur/sulfate than in plots subjected to the drilled treatments at Fort Saskatchewan in 1998 and at the Wostok/Andrew sites in both 1997 and 1998. It appears that sulfur/sulfate on the soil surface can act as a deterrent to oviposition by root maggot females; if so, this would explain the development of less root damage at both sites when sulfur was applied top-dressed, although we found no effects of application method on egg deposition or seed yield at Fort Saskatchewan.

In this study, data from the Fort Saskatchewan site determined that elemental sulfur applied in a powder formulation drilled in with the seed, and a prill formulation top-dressed on the soil surface, caused significant reductions in damage to taproots from feeding by root maggot larvae, but these reductions in root damage were not accompanied by increased seed yield. Similar results were obtained at Wostok in 1997. There was no apparent impact of ammonium sulfate and sprays of elemental sulfur on root maggot damage to canola taproots or seed yield. The Fort Saskatchewan and Wostok data on sulfur prills corroborate those of

Dosdall (1996) who found that applications of MF 101® prills at rates of 30 and 50 pounds per acre caused significant reductions in root maggot damage to canola in study sites near Warburg and Vegreville. Moreover, previous studies at Wostok determined that plants of both *B. napus* and *B. rapa* treated with MF 101® at rates of 20 and 50 pounds per acre had significantly less root damage at the end of the season than plants grown without sulfur additions or plants grown with sulfur at 10 pounds per acre (Dosdall 1997). In both previous studies, increases in seed yield occurred with an increase in application rate of MF 101®, but these increases were not significant statistically (Dosdall 1996, 1997). It is evident, therefore, that elemental sulfur is not effective under all circumstances for reducing damage to canola taproots from feeding by larval root maggots. Factors which may affect the efficacy of elemental sulfur for root maggot control include application rate, residual soil sulfate levels, and environmental factors. In the present study, lowest root damage values were usually found at the highest rates of application for all formulations of elemental sulfur, even though these may not have differed significantly from the controls. The study sites were deficient is soil sulfate content at the outset of the experiments and greatest reductions in root damage occurred with the powdered formulation of elemental sulfur, which would have been oxidized most readily to the sulfate form. Environmental factors, such as the amount of rainfall, soil type, and the abundance and composition of the soil microbe community may affect the rate at which elemental sulfur is oxidized to form sulfate, and these factors can also affect the rate of leaching of elemental sulfur to lower levels of the soil profile.

The mechanism by which sulfur acts to reduce plant damage from root maggot attack is unknown. Elemental sulfur oxidizes in the soil to form sulfate ($SO_4^{=}$), which can then be taken up by plants. The sulfate may have had a toxic effect on root maggot larvae, especially because larval root maggots are very soft-bodied insects. If the elemental sulfur had not oxidized completely in the soil, it may have acted as a contact insecticide to root maggot larvae. Applications of elemental sulfur can reduce pH levels in soils with poor or little buffering capacity, and this increase in acidity could negatively affect the survival or development of root maggot larvae. Alternatively, canola plants able to take up sufficient quantities of sulfate may have compensated for root maggot attack by producing larger taproots, which would have resulted in lower root damage ratings.

Except for the highest sulfur application rates of 100 pounds per acre, the rates used in this study, especially 25 and 50 pounds per acre, were consistent with the requirements of canola for this nutrient. Canola requires approximately 1.5 kg of sulfur to grow 100 kg of seed (Nyborg et al. 1971), so a 2000 kg per ha crop would require approximately 30 kg sulfur per ha (Grant and Bailey 1993). Soil tests performed at the study sites prior to seeding indicated that only approximately 25 kg per ha of sulfate were available in the soil. Karamanos and Janzen (1991) found that sulfur-bentonite (MF 101®) is not as readily available to plants in the short-term compared with finely divided elemental sulfur applied in suspension. Similarly, Noellemeyer et al. (1981) suggested that spring-applied elemental sulfur, with slow oxidation rates, would be of little value for canola production compared with ammonium sulfate. Therefore, the applications of sulfur prills used in this study, when added to the residual soil sulfur levels, are not indicative of the sulfate that was biologically available to plants, or in this case to root maggot larvae, because the prills likely could not be completely oxidized during the growing season. However, the elemental sulfur in the powdered formulation was present in particle sizes sufficiently small (35 μ) that they should have been oxidized during the season. The powdered sulfur, therefore, should have been biologically available to the canola plants as sulfate.

Economic Assessment of Root Maggot Control with Sulfur/Sulfate

For applications of sulfur or sulfate to be agriculturally acceptable, it is necessary that economic returns from reduced root maggot infestations and improved yields exceed the costs of the treatments. Consequently, an economic assessment was conducted to investigate whether this occurred in our study.

The current price for granular ammonium sulfate is $250.00 per tonne or $0.11 per pound. The price of elemental sulfur prills (MF 101®) is $300.00 per tonne or $0.13 per pound. The powdered elemental sulfur used in this study is not yet available commercially, but if so, it would probably be produced at a cost comparable to that of the prills of elemental sulfur ($0.13 per pound).

At Fort Saskatchewan in 1997, all application rates of ammonium sulfate drilled in with the seed resulted in improved yields relative to the control plots, and the improved gross returns from those yields exceeded the product costs (Table 1). Greatest improved gross returns per acre were achieved at an application rate of 40 pounds per acre ($32.08), but even the lowest improved gross returns at 25 pounds per acre ($5.73) were substantial. Drilled applications of powdered sulfur produced improved gross returns except when applied at 10 pounds per acre, and prills of MF 101® produced improved gross returns except when applied at 100 pounds per acre (Table 1). For top-dressed applications of ammonium sulfate, improved gross returns were achieved at application rates of 10, 25, and 40 pounds per acre but not at 50 pounds per acre. Top-dressed applications of powdered elemental sulfur were associated with improved gross returns for all rates of application except 50 pounds per acre, but when prills of elemental sulfur were top-dressed no improved economic returns were achieved regardless of application rate (Table 1).

In 1998 at Fort Saskatchewan, all drilled applications of ammonium sulfate resulted in improved gross returns. Gross returns increased with an increase in application rate and ranged from $15.06 per acre at the lowest application rate (10 pounds per acre) to $39.46 per acre at the highest rate (50 pounds per acre) (Table 2). No improved gross returns were achieved with drilled applications of sulfur powder in 1998, and for drilled applications of prills, improved gross returns were achieved only at the rate of 100 pounds per acre. Top-dressed applications of ammonium sulfate did not result in improved gross returns in 1998, but applications of 10, 50, and 100 pounds per acre of elemental sulfur powder were associated with improved gross returns ranging from $16.30 per acre at 10 pounds per acre to $23.74 at 50 pounds per acre. Top-dressed applications of sulfur prills produced improved gross returns for all application rates, and these ranged from $1.90 per acre at an application rate of 10 pounds per acre to $21.66 at 50 pounds per acre (Table 2).

At Wostok in 1997, application rates of ammonium sulfate of 10 and 25 pounds per acre, drilled in with the seed, resulted in improved yields relative to the control plots, and the improved gross returns from those yields exceeded the product costs (Table 3). Improved gross returns were similar for both application rates (ca. $47.00 per acre). Drilled applications of powdered sulfur produced improved gross returns at application rates of 10 and 100 pounds per acre of $0.78 and $10.76, respectively; in addition, drilled applications of sulfur prills at 10 and 50 pounds per acre produced improved gross returns of $7.50 and $9.98 per acre, respectively (Table 3). For top-dressed applications of ammonium sulfate, improved gross returns were achieved at application rates of 25, 40, and 50 pounds per acre, and top-dressed applications of powdered elemental sulfur were associated with improved gross returns for all rates of application. Prills of elemental sulfur were associated with improved gross returns at an application rate of 25 pounds per acre (Table 3).

At Andrew in 1998, none of the drilled or top-dressed applications of ammonium sulfate resulted in improved gross returns (Table 4). Improved gross returns were achieved with drilled applications of sulfur powder at rates of 10 and 25 pounds per acre, and with sulfur prills at rates of 10, 50, and 100 pounds per acre. Top-dressed applications of sulfur powder produced improved gross returns at application rates of 10 and 50 pounds per acre. Top-dressed applications of sulfur prills produced improved gross returns for application rates of 25, 50, and 100 pounds per acre, and these ranged from $28.12 per acre at an application rate of 100 pounds per acre to $67.79 at 25 pounds per acre (Table 4).

Although applications of ammonium sulfate were often associated with improved gross returns, it is not likely that this was related to root maggot infestations because ammonium sulfate did not affect mean root maggot damage ratings in either 1997 or 1998 (Figs. 5, 6, 7, 8). This product evidently enhanced plant vigour and the capability of canola plants to compensate for root maggot attack. Yield improvements associated with elemental sulfur powder and prills were often associated with decreased root damage ratings. For example, at Fort Saskatchewan in 1998, significantly less root maggot damage occurred to canola treated with top-dressed applications of elemental sulfur prills at 50 and 100 pounds per acre and here the improved gross returns amounted to $21.66 and $6.68 per acre, respectively. It should be noted, however, that this relationship was not consistent. In 1998, drilled application of elemental sulfur powder at 50 and 100 pounds per acre resulted in significant reductions in root maggot damage, but no improvements in seed yield were observed for these plots relative to the controls. It is evident, therefore, that interactions between sulfur application, root maggot damage, and canola seed yield are complex and producers may not always gain an economic benefit from sulfur applications. Nevertheless, previous research has clearly established that sulfur is an essential component in the profitable production of canola, and growers should always work to ensure adequate levels of this crop nutrient in agricultural soils.

Acknowledgements

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Table 1. Mean improved seed yields over control plots following additions of various sulfur/sulfate applications, the costs of the treatments, and the improved gross returns per acre for plots of *Brassica rapa* at the Fort Saskatchewan site in 1997.

Application Method	Treatment	Application Rate (lbs./acre)	Improved Yield Over Controls (bu./acre)	Costs per Acre*	Improved Gross Return/Acre**
Drilled	Ammonium Sulfate	10	1.10	$ 1.10	$ 7.70
		25	1.06	2.75	5.73
		40	4.56	4.40	32.08
		50	2.75	5.50	16.50
	Sulfur Powder	10	0.07	1.30	—
		25	1.28	3.25	6.99
		50	6.50	6.50	45.50
		100	1.98	13.00	2.84
	Sulfur Prills	10	2.97	1.30	22.46
		25	5.69	3.25	42.27
		50	7.34	6.50	52.22
		100	0.29	13.00	—
Top-Dressed	Ammonium Sulfate	10	0.33	1.10	1.54
		25	5.87	2.75	44.21
		40	6.13	4.40	44.64
		50	0.55	5.50	—
	Sulfur Powder	10	6.24	1.30	48.62
		25	2.79	3.25	19.07
		50	—	6.50	—
		100	5.18	13.00	28.44
	Sulfur Prills	10	—	—	—
		25	—	—	—
		50	—	—	—
		100	—	—	—

* Costs per acre = $0.11 per pound for ammonium sulfate and $0.13 per pound for prills and powder of elemental sulfur.

** Improved gross return per acre = improved yield over controls times the retail value of the harvested seed at $8.00 per bushel less the costs per acre of the sulfur/sulfate.

Table 2. Mean improved seed yields over control plots following additions of various sulfur/sulfate applications, the costs of the treatments, and the improved gross returns per acre for plots of *Brassica rapa* at the Fort Saskatchewan site in 1998.

Application Method	Treatment	Application Rate (lbs./acre)	Improved Yield Over Controls (bu./acre)	Costs per Acre*	Improved Gross Return/Acre**
Drilled	Ammonium Sulfate	10	2.02	$ 1.10	$ 15.06
		25	3.89	2.75	28.37
		40	4.52	4.40	31.76
		50	5.62	5.50	39.46
	Sulfur Powder	10	—	—	—
		25	—	—	—
		50	—	—	—
		100	—	—	—
	Sulfur Prills	10	—	—	—
		25	—	—	—
		50	—	—	—
		100	2.75	13.00	9.00
Top-Dressed	Ammonium Sulfate	10	—	—	—
		25	—	—	—
		40	—	—	—
		50	—	—	—
	Sulfur Powder	10	2.20	1.30	16.30
		25	—	—	—
		50	3.78	6.50	23.74
		100	4.11	13.00	19.88
	Sulfur Prills	10	0.40	1.30	1.90
		25	1.73	3.25	10.59
		50	3.52	6.50	21.66
		100	2.46	13.00	6.68

* Costs per acre = $0.11 per pound for ammonium sulfate and $0.13 per pound for prills and powder of elemental sulfur.

** Improved gross return per acre = improved yield over controls times the retail value of the harvested seed at $8.00 per bushel less the costs per acre of the sulfur/sulfate.

Table 3. Mean improved seed yields over control plots following additions of various sulfur/sulfate applications, the costs of the treatments, and the improved gross returns per acre for plots of *Brassica rapa* at the Wostok study site in 1997.

Application Method	Treatment	Application Rate (lbs./acre)	Improved Yield Over Controls (bu./acre)	Costs per Acre*	Improved Gross Return/Acre**
Drilled	Ammonium Sulfate	10	6.02	$ 1.10	$ 47.06
		25	6.20	2.75	46.85
		40	—	4.40	—
		50	—	5.50	—
	Sulfur Powder	10	0.26	1.30	0.78
		25	0.26	3.25	—
		50	—	6.50	—
		100	2.97	13.00	10.76
	Sulfur Prills	10	1.10	1.30	7.50
		25	—	3.25	—
		50	2.06	6.50	9.98
		100	—	13.00	—
Top-Dressed	Ammonium Sulfate	10	—	1.10	—
		25	6.31	2.75	47.73
		40	6.86	4.40	50.48
		50	4.52	5.50	30.66
	Sulfur Powder	10	2.20	1.30	16.30
		25	1.10	3.25	5.55
		50	4.85	6.50	32.30
		100	4.44	13.00	22.52
	Sulfur Prills	10	—	1.30	—
		25	1.10	3.25	5.55
		50	—	6.50	—
		100	1.21	13.00	—

* Costs per acre = $0.11 per pound for ammonium sulfate and $0.13 per pound for prills and powder of elemental sulfur.

** Improved gross return per acre = improved yield over controls times the retail value of the harvested seed at $8.00 per bushel less the costs per acre of the sulfur/sulfate.

Table 4. Mean improved seed yields over control plots following additions of various sulfur/sulfate applications, the costs of the treatments, and the improved gross returns per acre for plots of *Brassica rapa* at the Andrew study site in 1998.

Application Method	Treatment	Application Rate (lbs./acre)	Improved Yield Over Controls (bu./acre)	Costs per Acre*	Improved Gross Return/Acre**
Drilled	Ammonium Sulfate	10	—	$ 1.10	$ —
		25	—	2.75	—
		40	—	4.40	—
		50	—	5.50	—
	Sulfur Powder	10	0.33	1.30	1.34
		25	3.41	3.25	24.03
		50	—	6.50	—
		100	—	13.00	—
	Sulfur Prills	10	0.37	1.30	1.66
		25	—	3.25	—
		50	1.07	6.50	2.06
		100	2.64	13.00	8.12
Top-Dressed	Ammonium Sulfate	10	—	1.10	—
		25	—	2.75	—
		40	—	4.40	—
		50	—	5.50	—
	Sulfur Powder	10	1.10	1.30	7.50
		25	—	3.25	—
		50	4.44	6.50	29.02
		100	0.92	13.00	—
	Sulfur Prills	10	—	1.30	—
		25	8.88	3.25	67.79
		50	4.77	6.50	31.66
		100	5.14	13.00	28.12

* Costs per acre = $0.11 per pound for ammonium sulfate and $0.13 per pound for prills and powder of elemental sulfur.

** Improved gross return per acre = improved yield over controls times the retail value of the harvested seed at $8.00 per bushel less the costs per acre of the sulfur/sulfate.

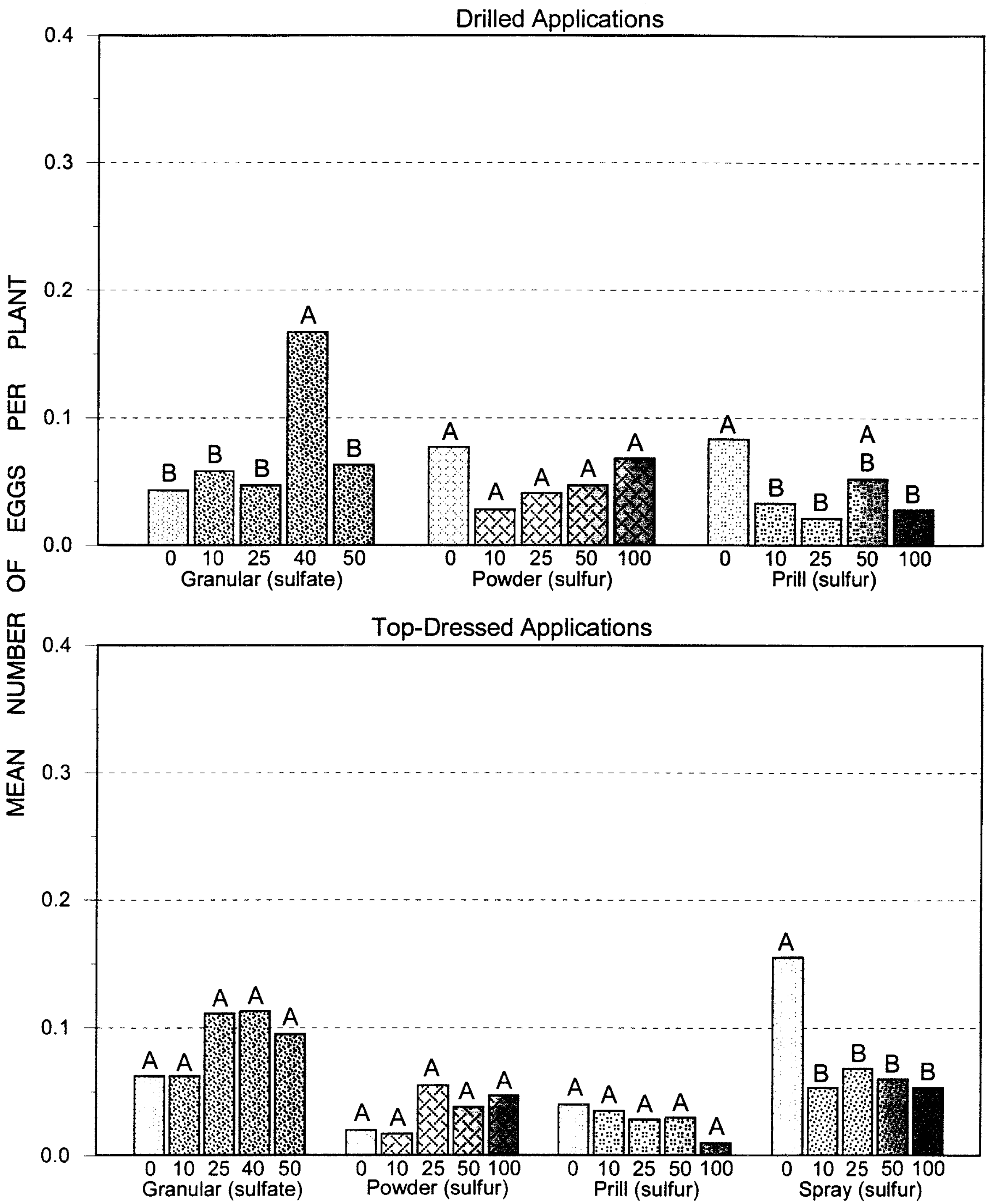

Fig. 1. Mean number of root maggot eggs per plant at the Fort Saskatchewan site in 1997 for experiments involving drilled and top-dressed applications of elemental sulfur and sulfate in various formulations (granular, powder, prill, and spray) and at various application rates. Letters on histograms indicate significance of differences among application rates within a formulation: means having the same letter indicate no significant differences using analysis of variance and Student-Newman-Keuls multiple comparisons.

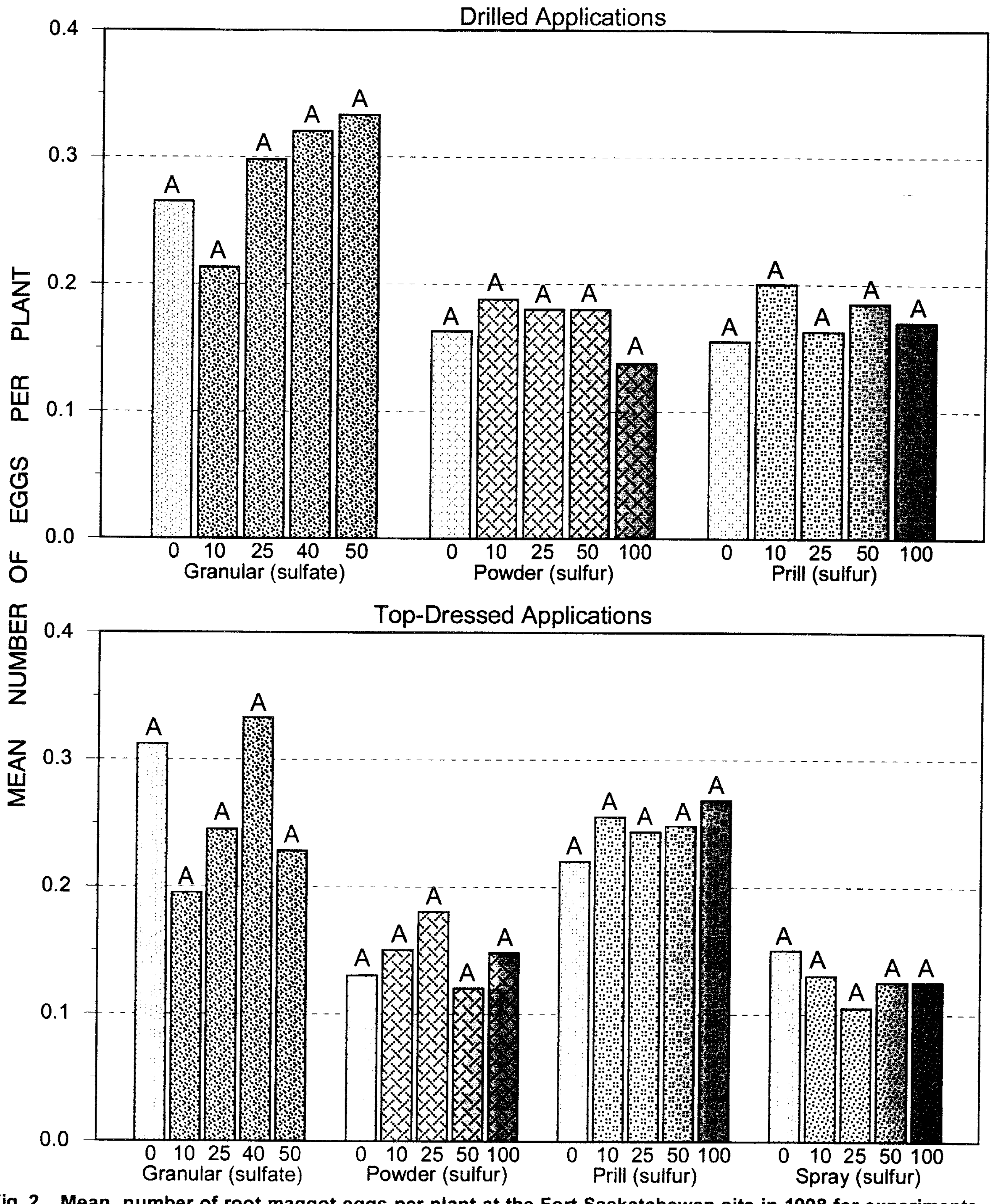

Fig. 2. Mean number of root maggot eggs per plant at the Fort Saskatchewan site in 1998 for experiments involving drilled and top-dressed applications of elemental sulfur and sulfate in various formulations (granular, powder, prill, and spray) and at various application rates. Letters on histograms indicate significance of differences among application rates within a formulation: means having the same letter indicate no significant differences using analysis of variance and Student-Newman-Keuls multiple comparisons.

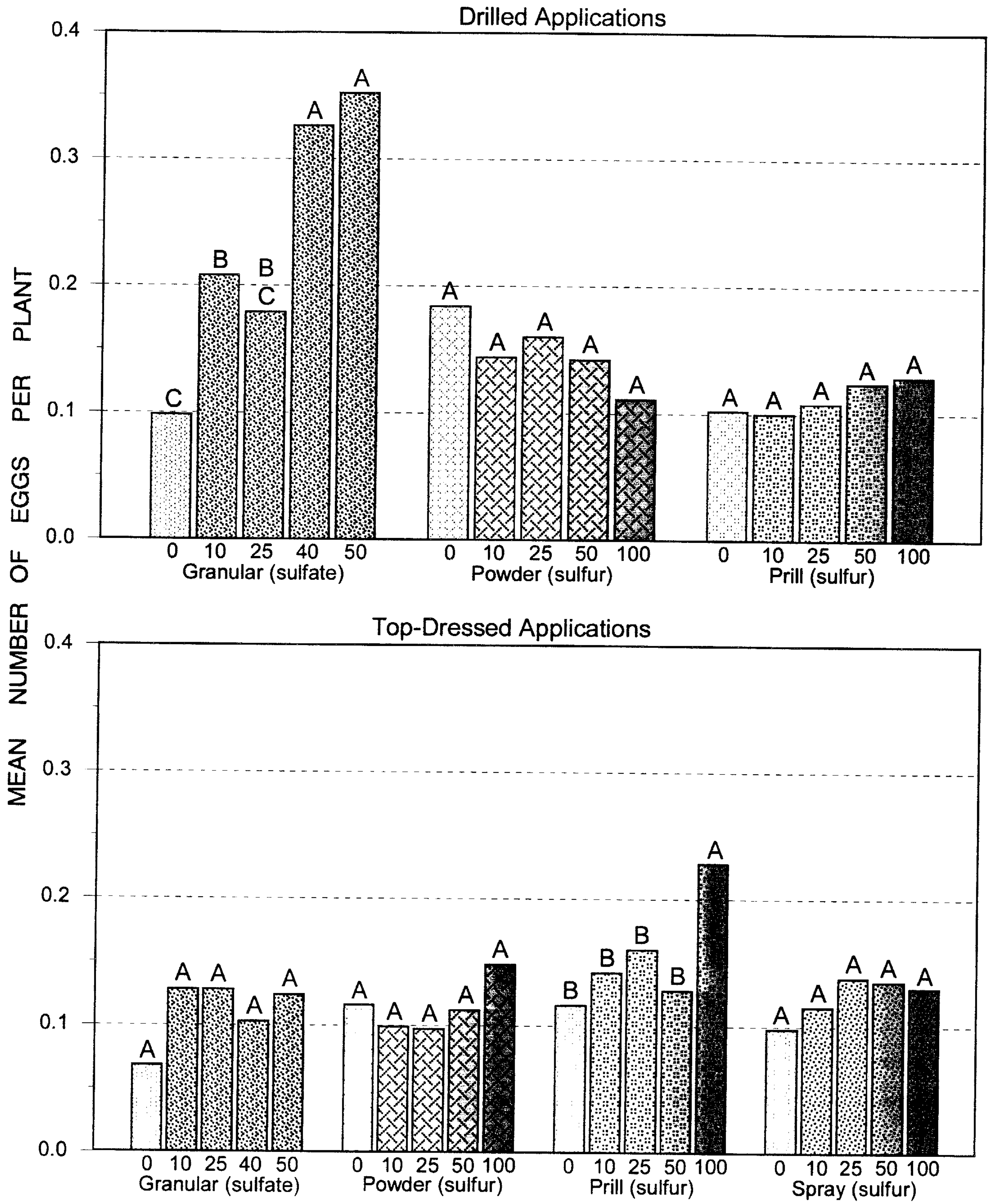

Fig. 3. **Mean number of root maggot eggs per plant at the Wostok site in 1997 for experiments involving drilled and top-dressed applications of elemental sulfur and sulfate in various formulations (granular, powder, prill, and spray) and at various application rates. Letters on histograms indicate significance of differences among application rates within a formulation: means having the same letter indicate no significant differences using analysis of variance and Student-Newman-Keuls multiple comparisons.**

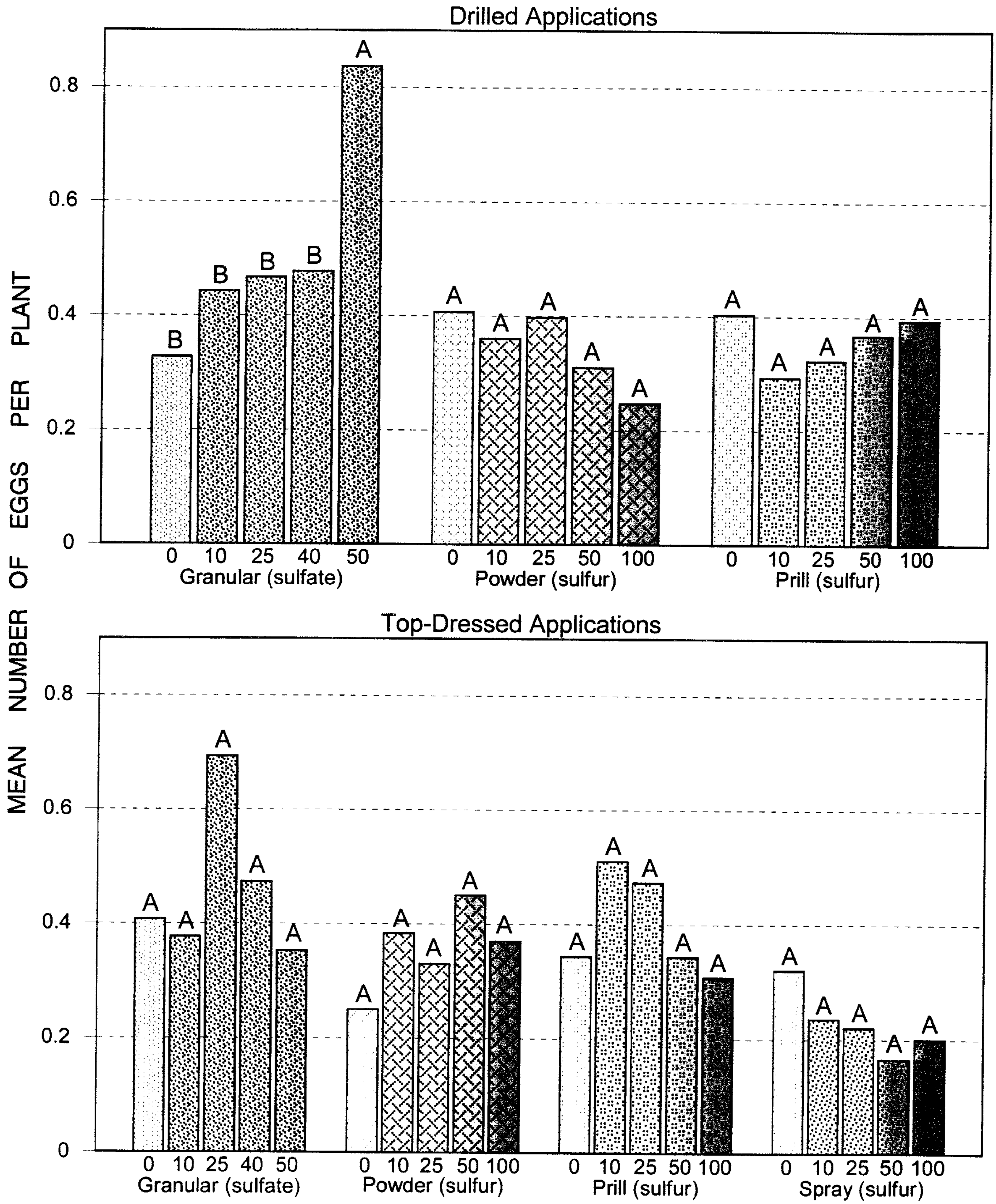

Fig. 4. Mean number of root maggot eggs per plant at the Andrew site in 1998 for experiments involving drilled and top-dressed applications of elemental sulfur and sulfate in various formulations (granular, powder, prill, and spray) and at various application rates. Letters on histograms indicate significance of differences among application rates within a formulation: means having the same letter indicate no significant differences using analysis of variance and Student-Newman-Keuls multiple comparisons.

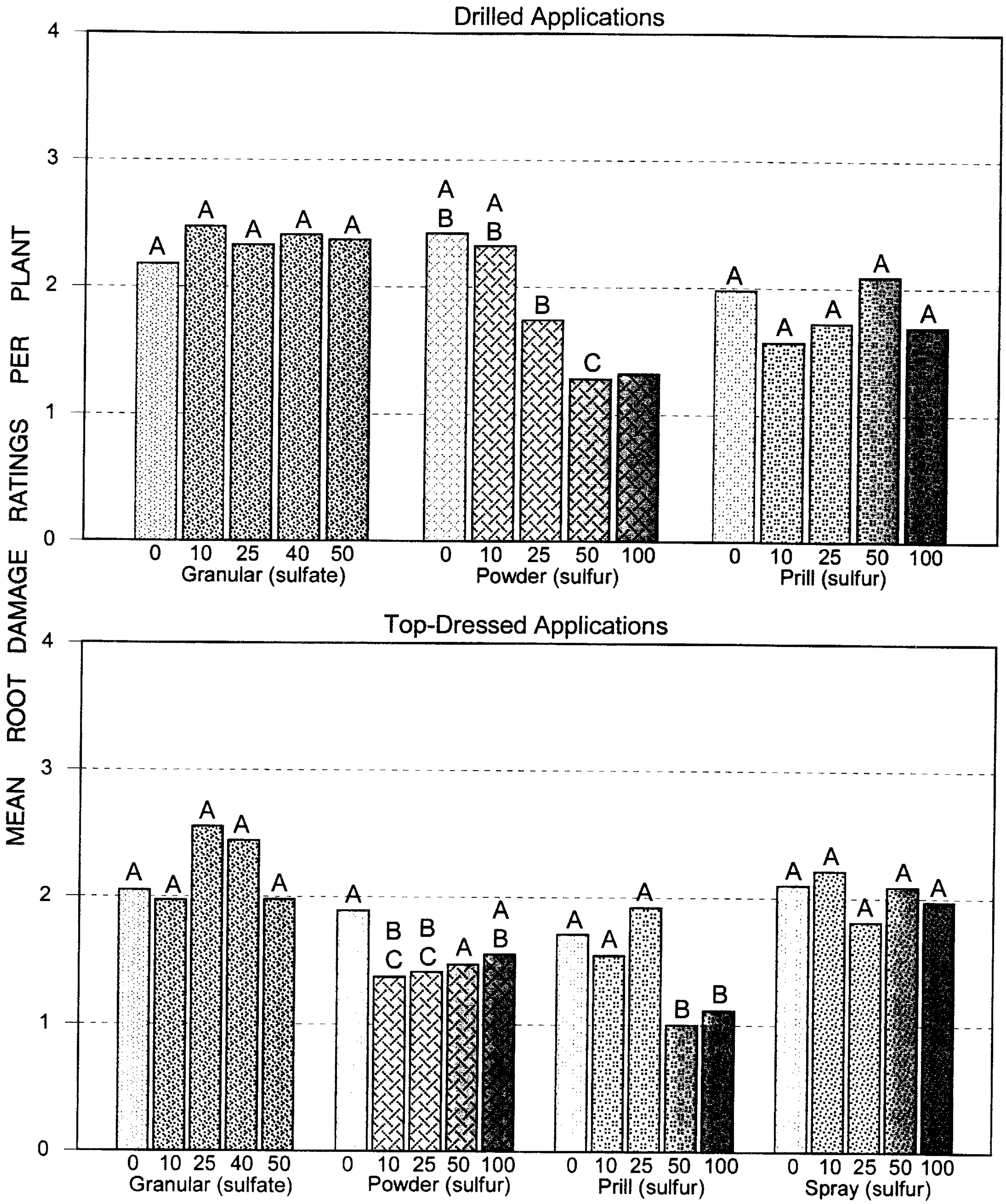

Fig. 5. Mean root maggot damage ratings per plant at the Fort Saskatchewan site in 1997 for experiments involving drilled and top-dressed applications of elemental sulfur and sulfate in various formulations (granular, powder, prill, and spray) and at various application rates. Letters on histograms indicate significance of differences among application rates within a formulation: means having the same letter indicate no significant differences using analysis of variance and Student-Newman-Keuls multiple comparisons.

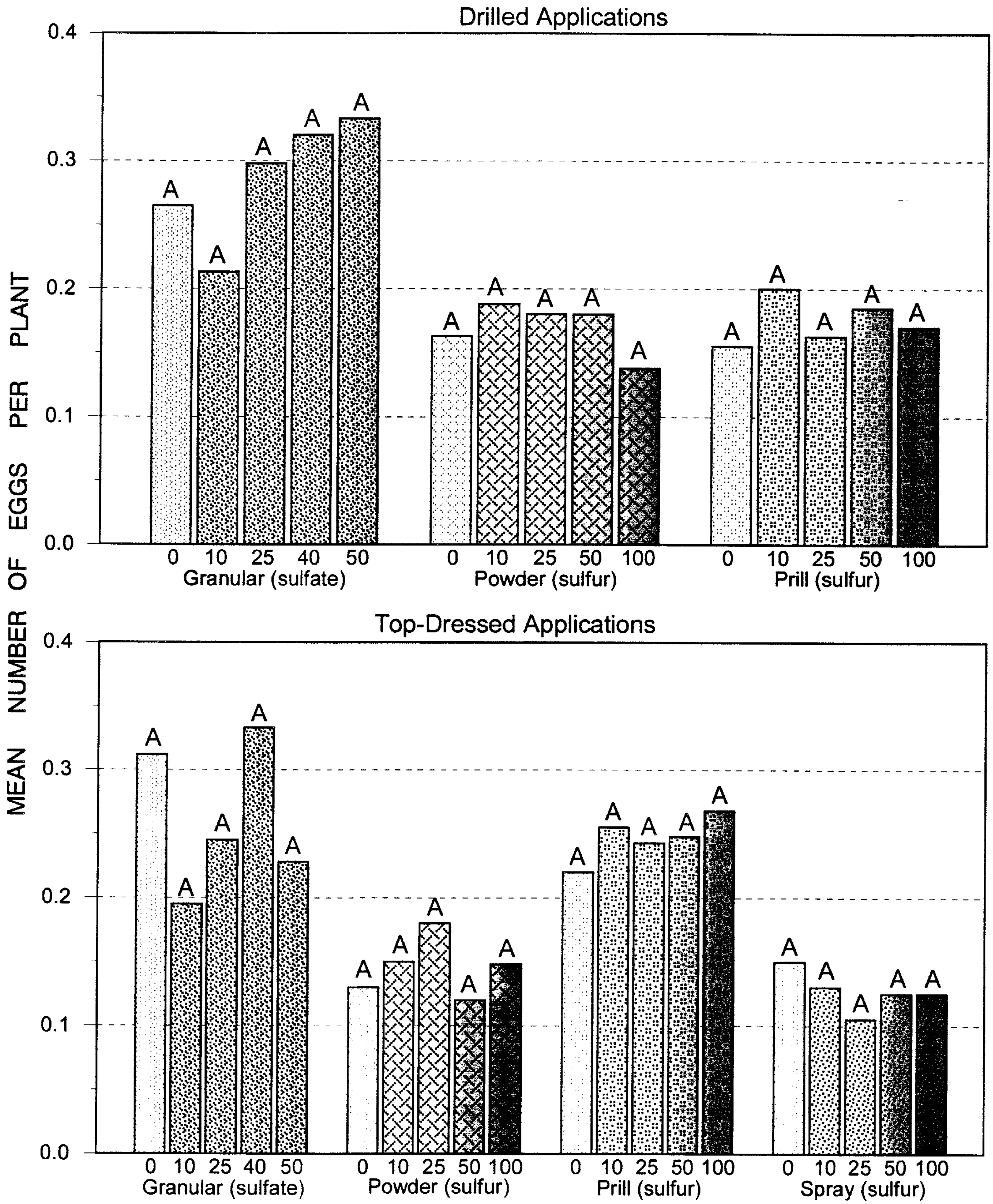

Fig. 6. Mean number of root maggot eggs per plant at the Fort Saskatchewan site in 1998 for experiments involving drilled and top-dressed applications of elemental sulfur and sulfate in various formulations (granular, powder, prill, and spray) and at various application rates. Letters on histograms indicate significance of differences among application rates within a formulation: means having the same letter indicate no significant differences using analysis of variance and Student-Newman-Keuls multiple comparisons.

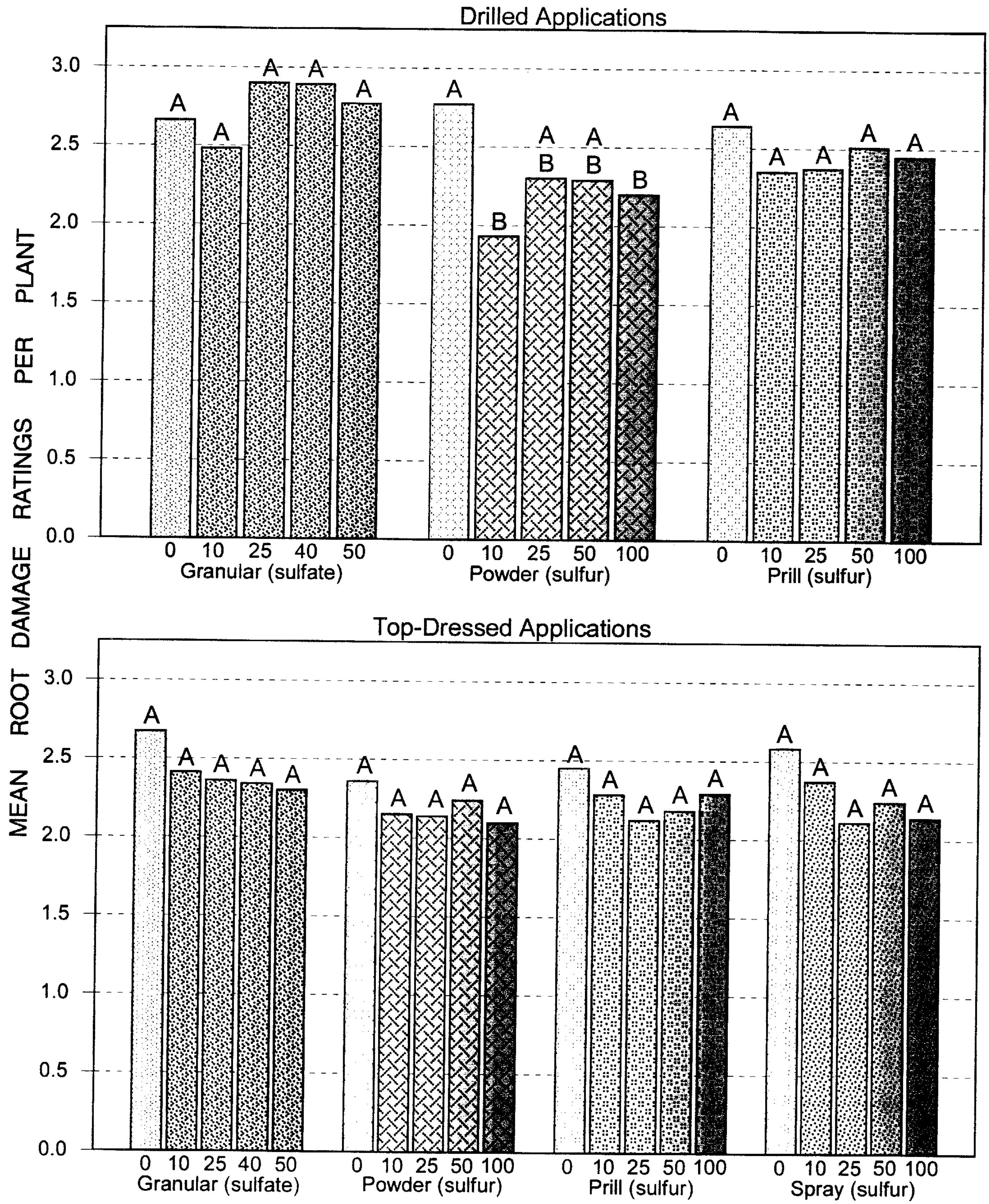

Fig. 7. Mean root maggot damage ratings per plant at the Wostok site in 1997 for experiments involving drilled and top-dressed applications of elemental sulfur and sulfate in various formulations (granular, powder, prill, and spray) and at various application rates. Letters on histograms indicate significance of differences among application rates within a formulation: means having the same letter indicate no significant differences using analysis of variance and Student-Newman-Keuls multiple comparisons.

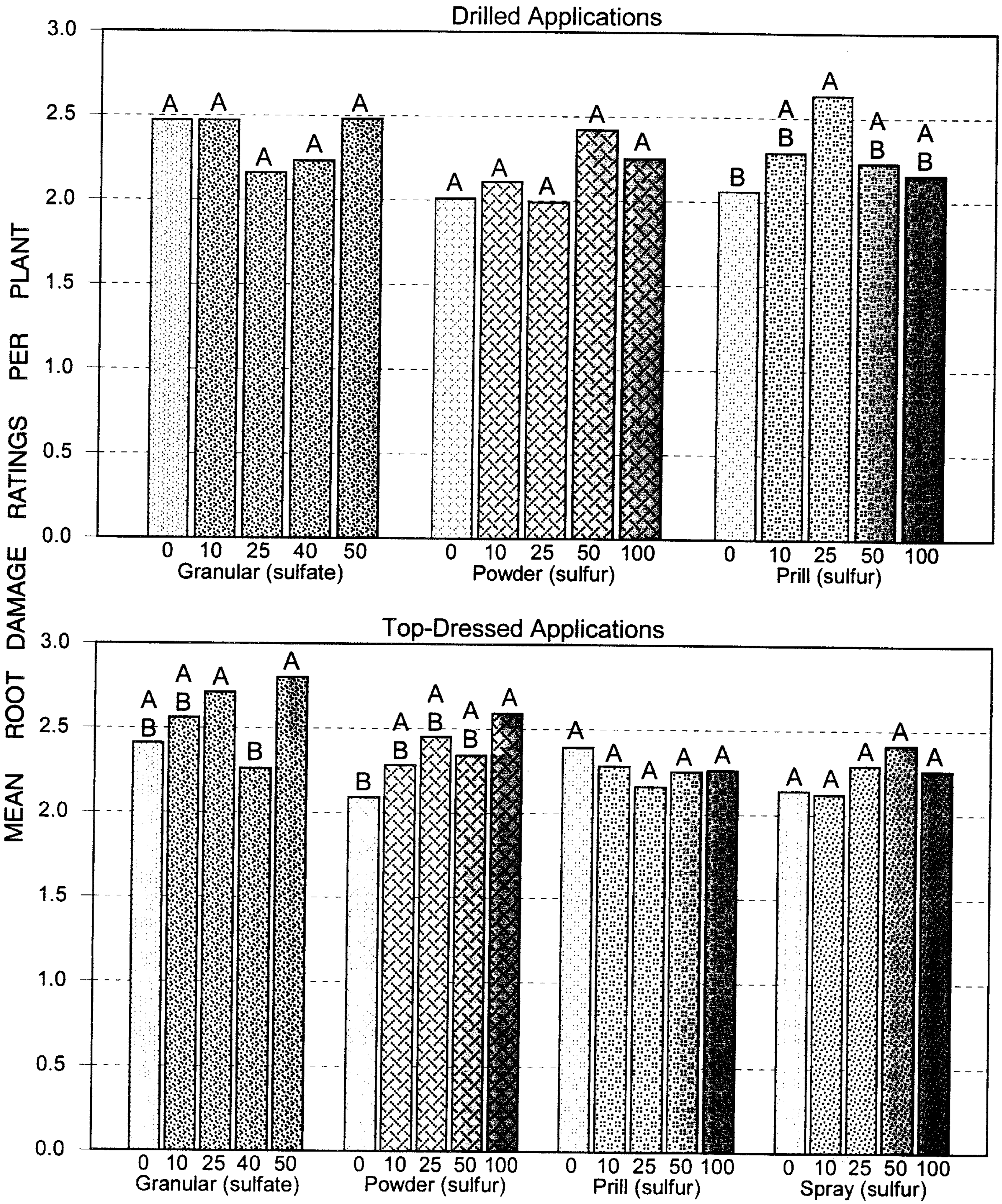

Fig. 8. **Mean root maggot damage ratings per plant at the Andrew site in 1998 for experiments involving drilled and top-dressed applications of elemental sulfur and sulfate in various formulations (granular, powder, prill, and spray) and at various application rates. Letters on histograms indicate significance of differences among application rates within a formulation: means having the same letter indicate no significant differences using analysis of variance and Student-Newman-Keuls multiple comparisons.**

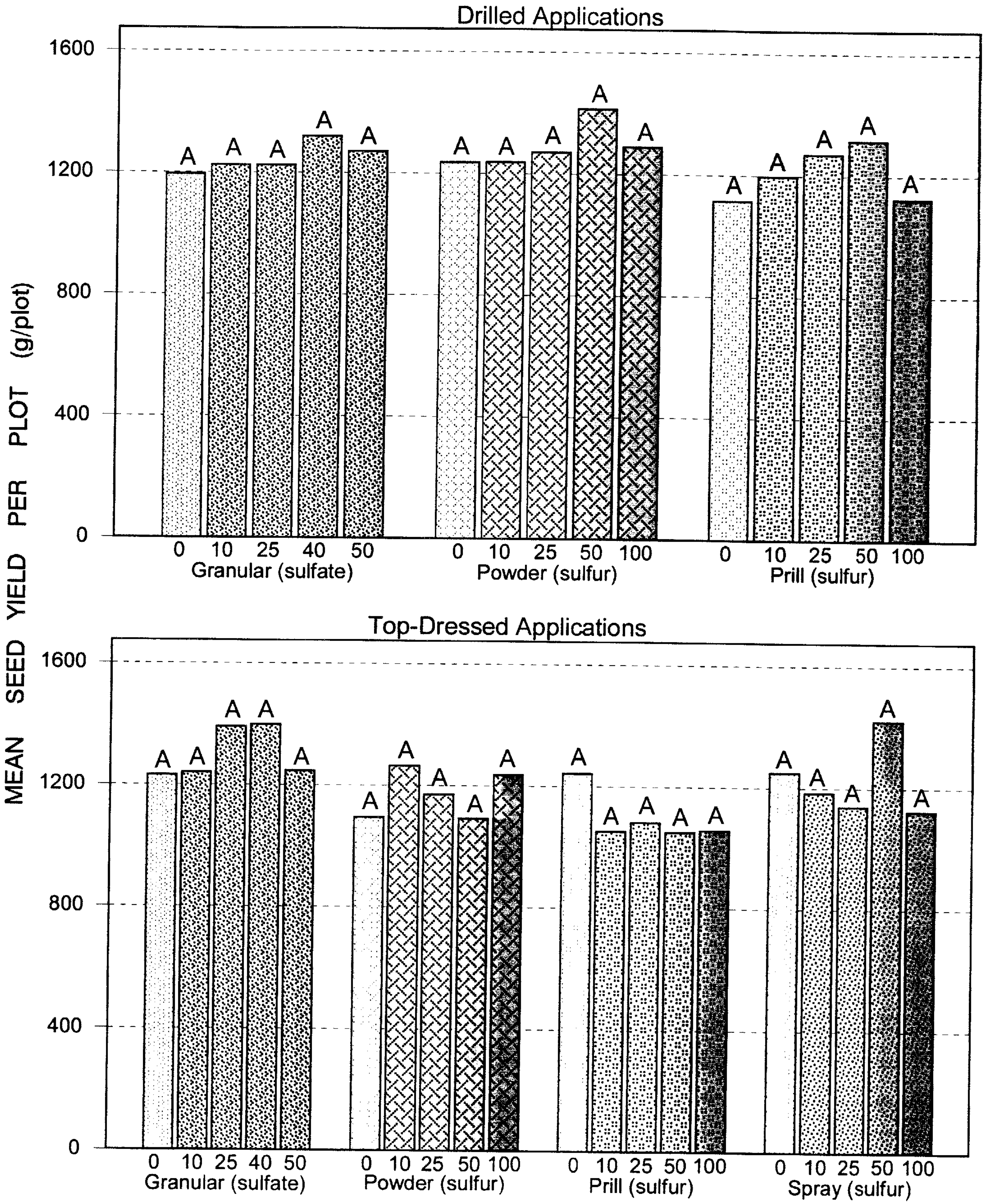

Fig. 9. **Mean seed yield per plot at the Fort Saskatchewan site during 1997 for experiments involving drilled and top-dressed applications of elemental sulfur and sulfate in various formulations (granular, powder, prill, and spray) and at various application rates. Letters on histograms indicate significance of differences among application rates within a formulation: means having the same letter indicate no significant differences using analysis of variance and Student-Newman-Keuls multiple comparisons.**

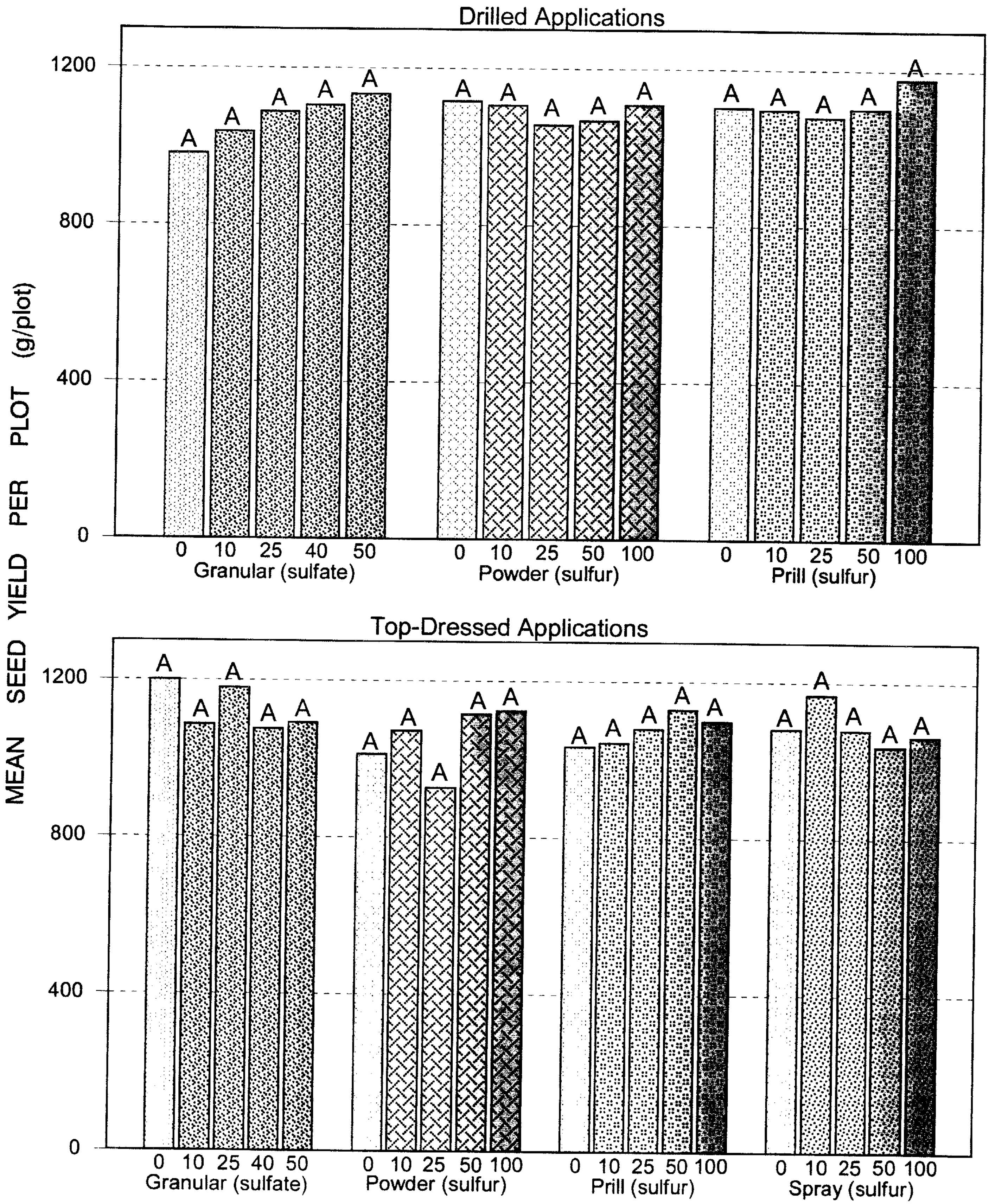

Fig. 10. Mean seed yield per plot at the Fort Saskatchewan site in 1998 for experiments involving drilled and top-dressed applications of elemental sulfur and sulfate in various formulations (granular, powder, prill, and spray) and at various application rates. Letters on histograms indicate significance of differences among application rates within a formulation: means having the same letter indicate no significant differences using analysis of variance and Student-Newman-Keuls multiple comparisons.

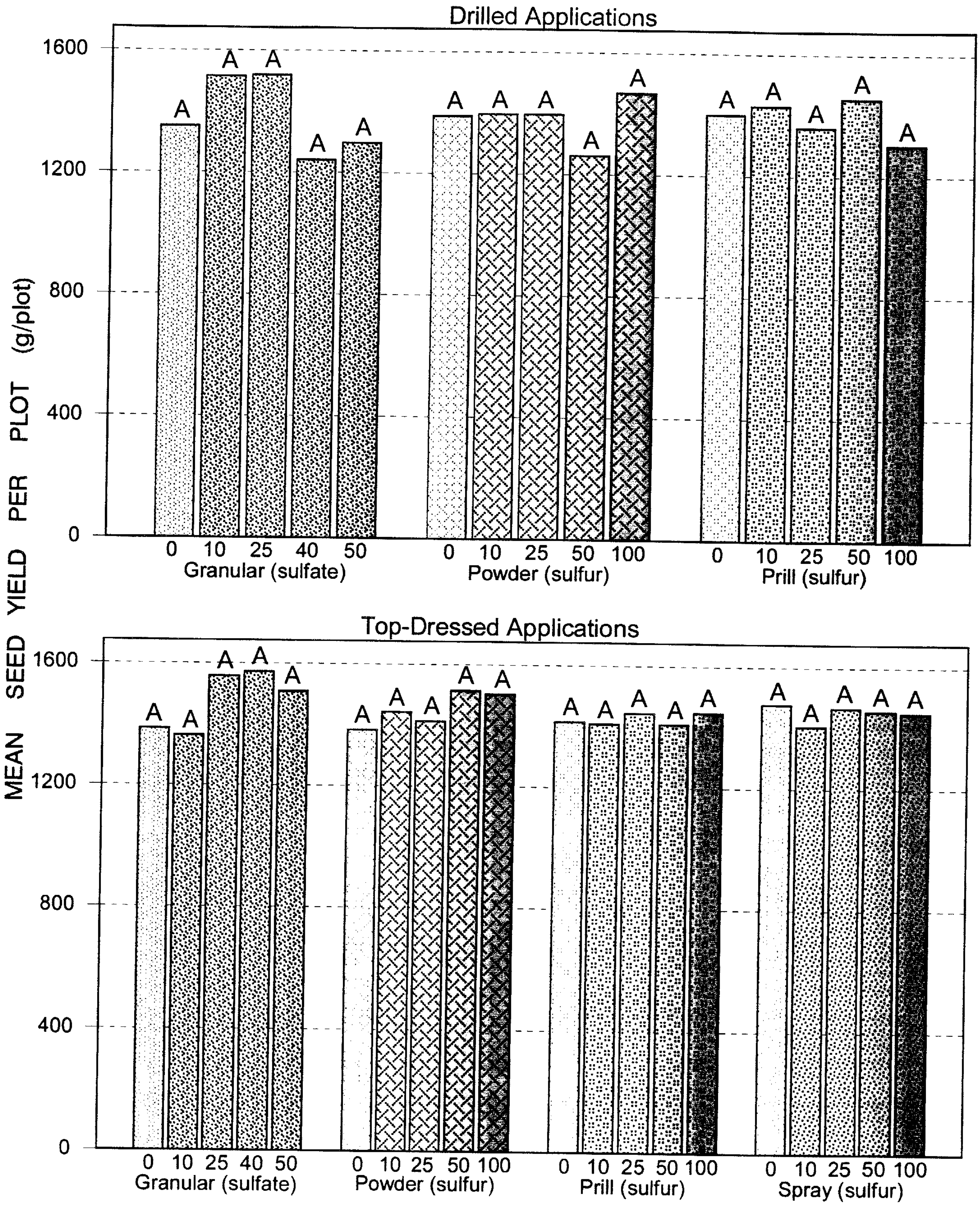

Fig. 11. Mean seed yield per plot at the Wostok site during 1997 for experiments involving drilled and top-dressed applications of elemental sulfur and sulfate in various formulations (granular, powder, prill, and spray) and at various application rates. Letters on histograms indicate significance of differences among application rates within a formulation: means having the same letter indicate no significant differences using analysis of variance and Student-Newman-Keuls multiple comparisons.

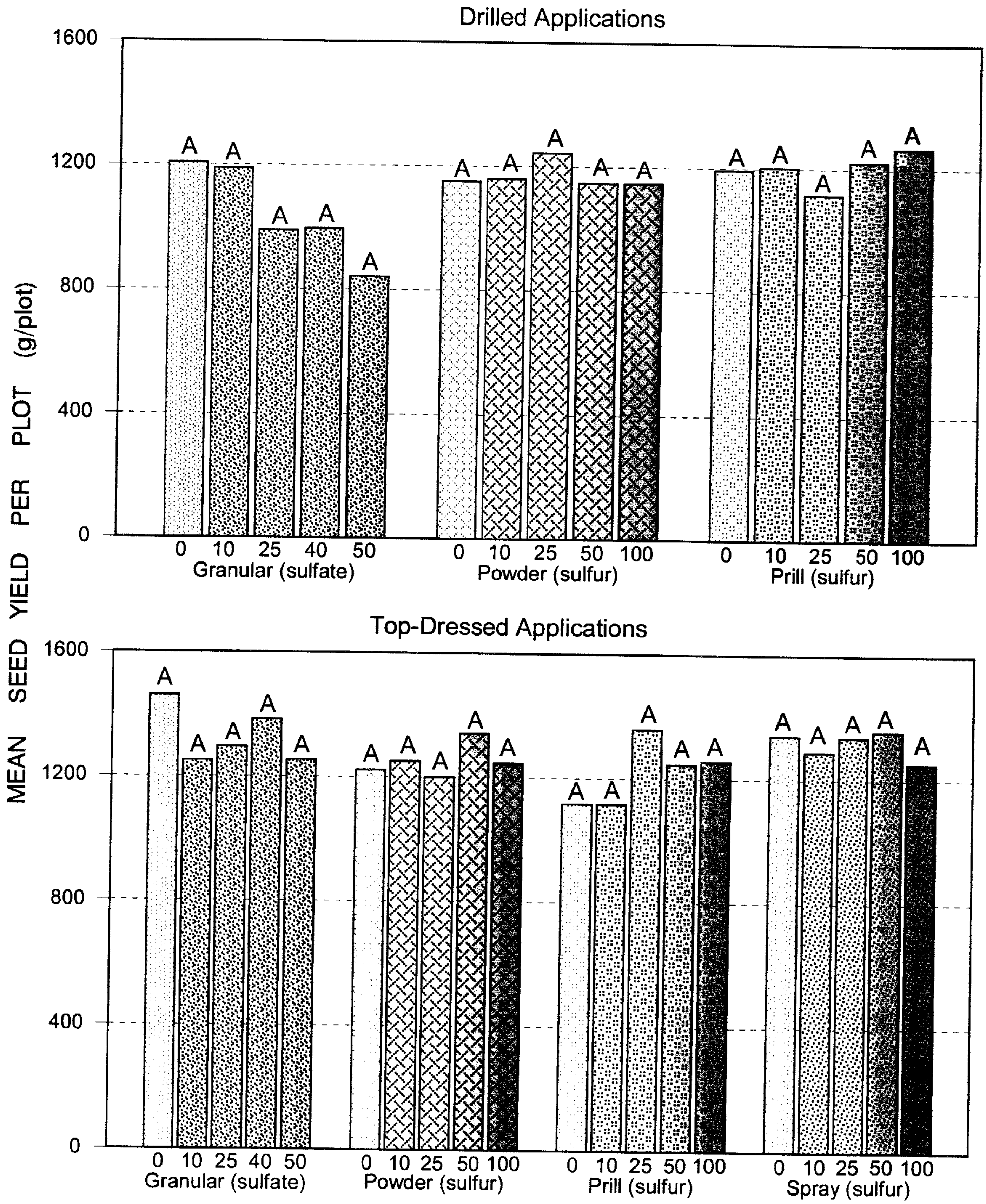

Fig. 12. Mean seed yield per plot at the Andrew site in 1998 for experiments involving drilled and top-dressed applications of elemental sulfur and sulfate in various formulations (granular, powder, prill, and spray) and at various application rates. Letters on histograms indicate significance of differences among application rates within a formulation: means having the same letter indicate no significant differences using analysis of variance and Student-Newman-Keuls multiple comparisons.