Sulfur-Coated Fertilizers for Controlled Release: Agronomic Evaluation

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Three greenhouse pot experiments were conducted to evaluate long-term crop response to uncoated and sulfur-coated urea (SCU), diammonium phosphate (SCP), and potassium chloride (SCK). With bermuda grass cut eight times at 2-week intervals, SCU gave more uniform uptake of N and yield of forage than did uncoated urea (U). At higher rates of application where luxury uptake of N from U occurred, SCU also gave greater total forage yield. Yield and uptake of K from SCK by three crops of corn, each grown for 6 weeks, resulted in the same patterns of controlled release as for SCU. At limiting rates, the only benefit from SCK over uncoated KCl was more uniform yield of forage; at higher rates, SCK also gave greater total forage yield. With sorghum clipped four times at 4-week intervals, SCP did not supply adequate P for optimum early growth. As a result, total yield of forage was less from SCP than from uncoated $(NH_4)_2HPO_4$ (DAP), although total uptake of P was similar from SCP and DAP.

I n the past nearly all controlled-release fertilizer research has been conducted with N sources. The purpose of this paper is to discuss briefly the potential for controlled release sources of N, P, and K, as well as to present some of our greenhouse results from sulfur-coated urea, $(NH_4)_2HPO_4$, and KCl. Potential benefits from controlled-release fertilizers include: more efficient utilization of plant nutrient by the crop; reduction in leaching, denitrification, and volatilization losses; decreased toxicity, as compared to soluble sources; and longer lasting, thus requiring less frequent application.

Efficiency of Nutrient Utilization. Uptake of N from soluble sources may be very rapid and often results in high concentrations of N in the tissue soon after fertilizer application. With forage crops, early clippings often contain more N than is actually required for optimum crop growth. With normal clipping procedure, this luxury consumption of N results in less available N for crop growth later in the season. Thus, one objective of controlled-release N sources is to supply N in accordance with normal crop requirements. If growth conditions are satisfactory through the season, the result is more forage per unit of total N uptake by the crop. With annual crops like corn, excessive uptake of N early in the season is of less importance, since there is only one harvest and N in the forage tissue may be translocated to the developing grain as the crop matures.

Soluble K is also readily absorbed and may accumulate in plant tissue to levels far greater than the actual crop requirement. Thus, a theoretical case for controlled-release K exists, particularly for forage crops, based on the same principles as for N above.

As regards P sources, most crops require high concentrations of available P early in their growth cycle. When water-soluble P sources are applied to soil, maximum availability comes soon after dissolution, with a rapid decrease in availability as reaction products of lower water solubility form. Thus, the normal distribution pattern of soluble P sources fits the need of most crops. On this basis, benefit from controlled-release P may be small or even negative.

Reduction in Nutrient Losses. Nitrate-N, whether applied directly or derived from ammonium or organic sources by nitrification, is highly mobile in soil. Under high rainfall conditions without a growing crop on the land, losses of N to drainage water may be large. With controlled-release N sources, these losses may be partially controlled, since that portion not yet dissolved is not subject to leaching loss from occasional heavy rainfall. With continuous leaching, a situation seldom seen outside the laboratory, similar losses might be expected from soluble and controlled-release sources, the only difference lying in the time-loss pattern.

Nitrogen may also be lost from the soil by denitrification during periods of flooding, provided oxidizable organic matter is present. With controlled-release N sources, that portion not yet dissolved and nitrified is not subject to loss and may become available to the crop as more favorable soil conditions for plant growth develop. Similarly, surface-applied N sources, particularly urea, may lose substantial amounts of NH_3-N to the atmosphere. Since maximum losses occur from single heavy applications where release of NH_3 exceeds the capacity of crop or soil to absorb it, controlled-release sources may be expected to reduce, but not entirely eliminate, losses of N by this route.

Since P is immobile, not volatile, and is not subject to volatilization losses during flooding, one would not expect loss reduction benefits from controlled-release P sources under these conditions. In contrast, K is relatively mobile in acid sands under high rainfall conditions, particularly following heavy applications of ammonium salts. Under these conditions, reduction in loss of K to drainage water may be expected from controlled-release K sources.

Decreased Toxicity. Toxicity of soluble N fertilizers to many crops, particularly seedlings, may be produced by high ionic concentrations resulting from rapid dissolution of soluble fertilizers or from evolution of NH_3 by hydrolysis of certain salts, particularly urea. When these factors are controlled by any slow-release mechanism, reduction in toxicity may be expected.

Phosphate sources are seldom toxic to crops, with the exception of $(NH_4)_2HPO_4$, which sometimes causes seedling damage when row-placed. In this case, toxicity is related to NH_3, not the phosphate ion. On this basis, coating or some other slow-release mechanism may reduce toxicity of NH_3, but would not be expected to have any beneficial effect on use of P. In some cases, soluble K salts may be toxic if ionic concentration is high enough to interfere with water uptake by the crop. On these rather rare occasions, controlled-release K might be beneficial.

Frequency of Application. Split applications of soluble N or K sources often give increased crop yield, as well as im-

Table I. Nutrient Content and Dissolution Characteristics of Coated Fertilizers

Source of nutrient[a]	Symbol	Coating, wt %					% Dissolution in water at 100° F		Nutrient content, %			Experi-ment no.
		S	Wax	Micro-bicide	Condi-tioner	Total	1 day	7 days	N	P	K	
Sulfur-coated urea	SCU	15.2	3.0		1.0	19.2	1	2	38.1			1
Sulfur-coated (NH₄)₂HPO₄	SCP	10.4	3.0	0.5	1.0	14.9	5	5	15.5	17.1		2
Sulfur-coated KCl	SCK	24.0	3.0	0.3	1.7	29.0		23			36.5	3
Uncoated urea	U						100		46.0			1
Uncoated (NH₄)₂HPO₄	DAP						100		18.2	20.2		2
Uncoated KCl	KCl						100				51.5	3

[a] All sources screened to −6 +10 mesh granule size.

provement in the seasonal distribution of yield. This is particularly true of forage crops. Similar benefits may be expected from controlled-release sources, provided they release plant nutrients in a pattern similar to split applications. At the same time, cost of application may be reduced by a single application of controlled-release fertilizer, as compared to split applications of soluble sources. Similarly, long-term tropical crops, such as sugar cane and pineapples, require growth periods as long as 2 years. With these crops, benefits from effective controlled-release sources of N and K may be large, as compared to several applications of soluble sources.

Since split applications of P are not required under most annual cropping systems, one would not expect these benefits from controlled-release P sources.

As indicated above, considerable potential exists for controlled-release sources of N and K, while similar P sources may not be beneficial. With this in mind, how can we develop better controlled-release fertilizers? Three common routes are available to us, including: biodegradation of organic compounds yielding soluble N (ureaformaldehyde, UF); preparation of compounds low in water solubility which yield available N upon dissolution and hydrolysis of granules (isobutylidene diurea, IBDU); and coating of soluble sources to yield controlled-release N by degradation of the coatings and/or diffusion of soluble N through pores in the coating (sulfur-coated urea, SCU). Our research at the National Fertilizer Development Center has been concentrated on the latter approach for three common-sense reasons: sulfur coatings sealed with microcrystalline wax are effective; the coating materials are relatively inexpensive; and the residue of S left after dissolution of soluble constituents becomes available for crop use.

Methods for preparing small amounts of SCU in the laboratory have been reported (Rindt et al., 1968). A pilot plant procedure for preparation of larger amounts of S-coated urea (SCU), S-coated (NH₄)₂HPO₄ (SCP), and S-coated KCl (SCK) is described in a companion paper, this symposium (Blouin et al., 1971). Results from field testing SCU at Muscle Shoals, Ala. (Allen et al., 1968; Mays and Terman, 1969a,b; Mays, 1970) show conclusively that SCU is a superior source of N for forage grasses. With Kentucky 31 fescue and Coastal bermuda grass, similar total yield and seasonal distribution of forage production were obtained with a single application of SCU, as compared to split applications of uncoated urea or NH₄NO₃. Greenhouse and laboratory studies (Allen et al., 1971) show that release of N from SCU may be controlled by coating weight, placement, microbicides, time, and temperature. In the range of 15–25% coating weight, dissolution was most rapid with light coatings mixed with the soil and slowest with heavy coatings in surface placement. Addition of microbicides to the wax sealant further delayed release of N mixed with the soil, but had little

effect on the dissolution of surface-placed granules. Tests conducted with soil in controlled environment regimes showed that SCU (20% coating) remained almost intact for 16 weeks at 10° C, while dissolution was nearly complete in 5–8 weeks at 20 and 30° C. Similarly, flooding the soil very much decreased the rate of dissolution of SCU, as compared to well aerated soil (Giordano and Mortvedt, 1970).

MATERIALS AND METHODS

Nutrient content and dissolution characteristics of experimental fertilizers are shown in Table I. All coated products were prepared by the Applied Research Branch, TVA (Rindt et al., 1968).

Greenhouse Procedure. Three greenhouse experiments were conducted to evaluate SCU, SCP, and SCK under long-term cropping conditions. Mountview silt loam, an acid (pH 5.0) infertile soil collected near Lawrenceburg, Tenn., was used in all experiments. For Experiments 1 and 3, bulk lots were limed to pH 6.3 with a 2/1 mixture of CaCO₃ and MgCO₃ and fertilized with adequate amounts of other nutrients prior to cropping for 4 weeks with corn (Zea mays L.) in the greenhouse to deplete the soil to very low levels of available N or K, thus increasing the response to these nutrients by the subsequent crop. The corn crop was then removed and the soil processed in a soil shredding machine.

EXPERIMENT 1. Additional P, K, and micronutrients were applied at nonlimiting levels and the soil, depleted of N as above, was placed in plastic pots (6.25 kg of dry soil/pot). N sources to supply 500 or 1000 mg N/pot (80 or 160 ppm) were mixed with the soil prior to seeding common bermuda grass (Cynodon dactylon) on June 23, 1967. Beginning on July 19, forage was clipped at 5 cm above the soil at 2-week intervals until eight clippings were harvested. Forage from each clipping was dried, weighed, and analyzed for N by individual replicate. All treatments were replicated three times.

EXPERIMENT 2. Mountview soil was limed to pH 6.5 with a 2/1 mixture of CaCO₃ and MgCO₃, and nonlimiting levels of N, K, and micronutrients were mixed with the soil, along with P sources to supply 100 or 400 mg P/pot (4.5 kg of dry soil) prior to planting sorghum (Sorghum sp., variety Green M) on July 26, 1968. Forage was harvested four times by clipping at 10 cm above the soil at 4-week intervals. Additional N and K were supplied as solutions after each clipping. Forage was dried, weighed, and analyzed for P by individual replicate. All treatments were replicated three times.

EXPERIMENT 3. Mountview soil, depleted of K as above, was supplied with additional lime, nonlimiting levels of N, P, and micronutrients and K sources were mixed with the soil to supply 200 or 800 mg K/pot (3 kg dry soil) prior to planting corn on December 17, 1969. Forage was harvested by clipping at ground level after 6 weeks of growth (February 11, 1970). A second crop was planted on February 20 without
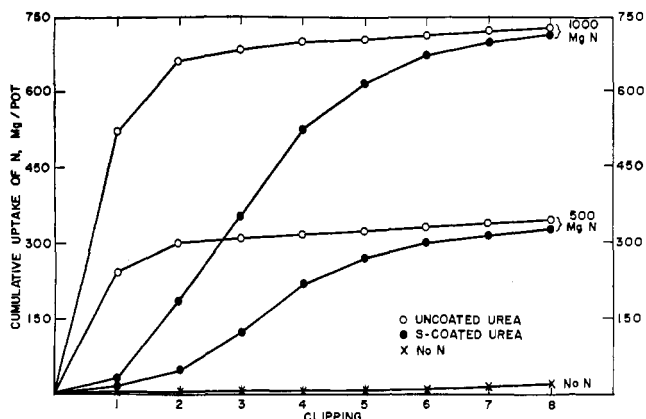
Figure 1. Cumulative uptake of N by bermuda grass (clipped eight times at 2-week intervals), as affected by rate and source of applied N (Experiment 1)
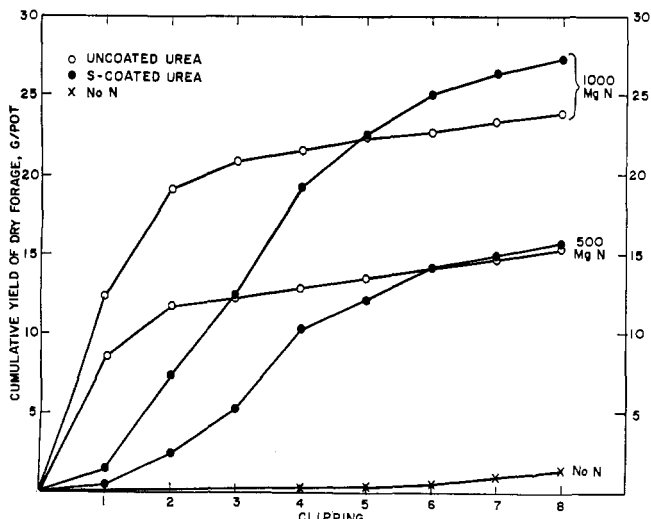

Figure 2. Cumulative yield of forage by bermuda grass (clipped eight times at 2-week intervals), as affected by rate and source of applied N (Experiment 1)
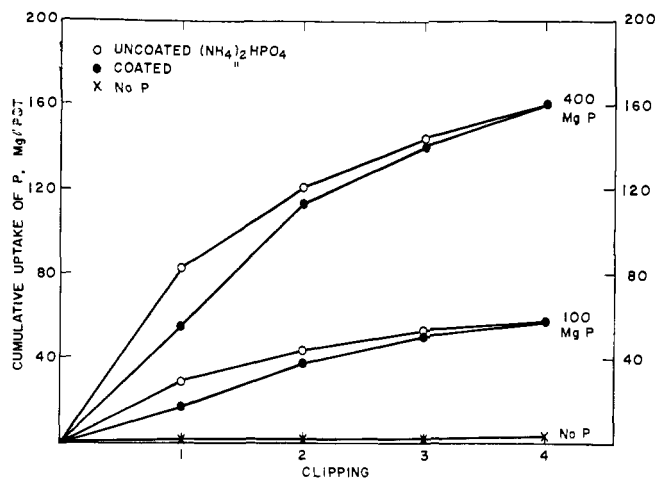

Figure 3. Cumulative uptake of P by sorghum (clipped four times at 4-week intervals), as affected by rate and source of applied P (Experiment 2)
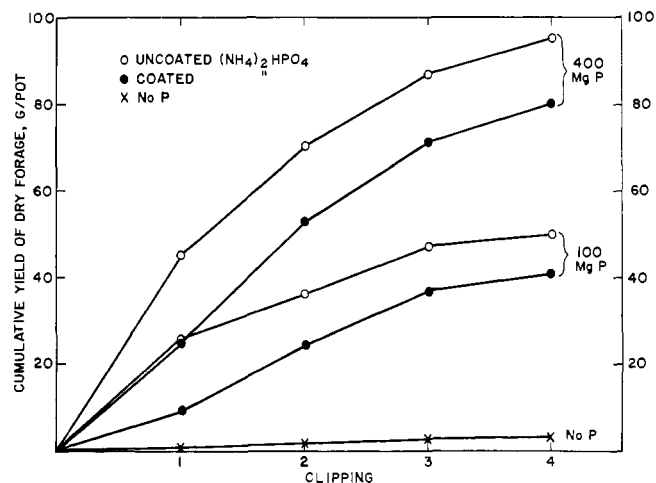

Figure 4. Cumulative yield of forage by sorghum (clipped four times at 4-week intervals), as affected by rate and source of applied P (Experiment 2)

tilling the soil and forage was harvested on April 3. A third crop was planted and harvested on April 15 and May 26, respectively. Additional N, P, and S were supplied in solution for optimum growth of crops 2 and 3. Forage from all crops was dried, weighed, and analyzed for K by individual replicate. All treatments were replicated three times.

RESULTS AND DISCUSSION

EXPERIMENT 1. Cumulative uptake of N by eight clippings is shown in Figure 1. At either rate of application, uptake from urea (U) was very rapid and almost all available N was taken up by the first two clippings. With SCU, uptake was very small in clipping 1, after which release was remarkably uniform, as shown by the smooth cumulative uptake curves. Since total uptake values were similar for U and SCU, it is assumed that dissolution of SCU was complete in 16 weeks. In this comparison, N sources were mixed with the soil; thus, losses of NH_3-N from either source were minimized. Mixing 20% U with SCU (results not shown) resulted in greater uptake by clipping 1 and eliminated the lag in availability of N caused by slow initial dissolution of SCU.

Comparison of these results with yield data (Figure 2) shows almost identical yield and uptake curves at the lower rate of application. It is thus apparent that the supply of N

was a limiting factor throughout the growth period and all available N was reflected in increased forage yield. Thus, at limiting levels of N, the only benefit from SCU was much more uniform crop growth, which was maintained over a much longer period, as compared to U. In contrast, at the higher rate of N, yield of forage from SCU was greater than from U. Since early clippings had very high N contents, it is assumed that luxury uptake of N from U occurred at the 1000 mg rate of application. Since clippings were harvested at regular intervals, the excess N from early clippings was "wasted" and was not available for later clippings. Thus, at the higher rate of application, SCU gave much more uniform forage production, as well as greater total yield, as compared to U.

EXPERIMENT 2. Cumulative uptake of P by four clippings of sorghum is shown in Figure 3. At both rates of application, uptake of P by clipping 1 was much less from SCP, as compared to water-soluble $(NH_4)_2HPO_4$ (DAP). Later clippings compensated for the initial lag in P availability from SCP and total uptake in four clippings was similar from both sources, indicating complete dissolution of SCP in 16 weeks. Comparison of uptake with forage yields (Figure 4) shows relatively poor response to SCP by clipping 1. This result clearly reflects the lack of sufficient available P from SCP
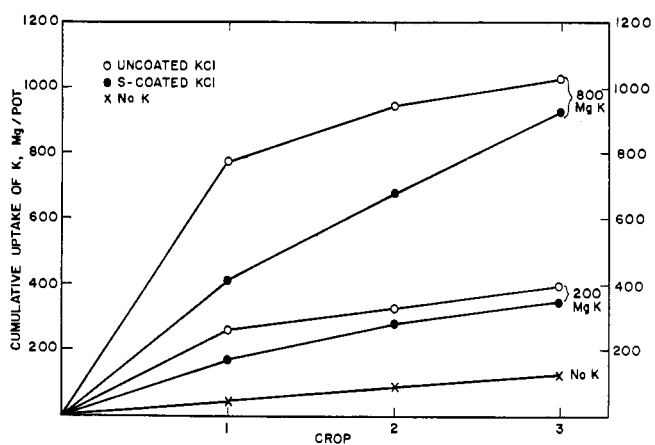
Figure 5. Cumulative uptake of K by three crops of corn (each of 6-weeks duration), as affected by rate and source of applied K (Experiment 3)
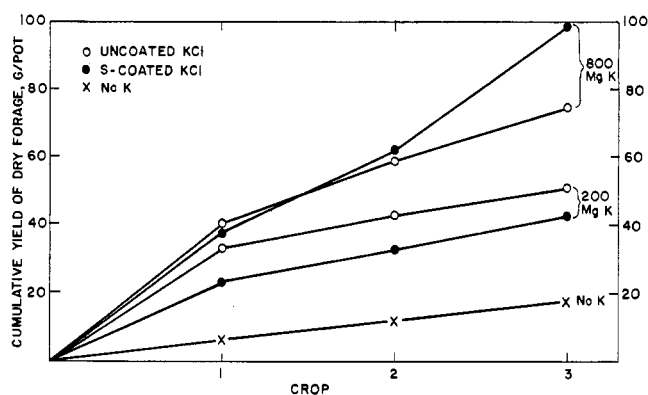

Figure 6. Cumulative yield of forage by three crops of corn (each of 6-weeks duration), as affected by rate and source of applied K (Experiment 3)

growth throughout the experiment, and all available K was reflected in forage growth. Thus, the slightly lower total yield from SCK may be a rate effect (uptake values suggested incomplete dissolution of SCK in 18 weeks). In contrast, SCK at the 800-mg rate produced 30% more forage in three crops than did KCl. This extra yield from SCK is clearly related to effective control of luxury uptake of K in crop 1. As a result, more K was available for crops 2 and 3 and this greater residual effectiveness of SCK resulted in greater total yield, as compared to KCl. These results suggest the same mechanism of controlled-release as already discussed for SCU. At limiting levels of K, the only benefit from SCK was more uniform forage production; at higher rates, where luxury consumption of K from KCl occurred, SCK gave more uniform crop response, as well as increased total yield.

CONCLUSIONS

Results reported here clearly suggest benefits from SCU and SCK, while SCP may not be promising. These conclusions are in agreement with theoretical considerations discussed earlier. As regards controlled-release N and K sources, more uniform and longer sustained forage production may be expected from a single application, as compared to soluble sources. At high rates of application where luxury consumption of N or K occurs from soluble sources, controlled-release sources may yield more forage, as well as modify the seasonal distribution of crop yield. In pot experiments with optimum water management, it has not been possible to measure potential benefits from reduction in losses by leaching or denitrification. However, in similar experiments where drainage losses were measured, SCU and SCK supplied less nutrient to the drainage water than did soluble sources of N and K, and the loss was related to the rate of dissolution of coated products (Terman and Allen, 1971).

In consideration of the above, SCU and/or SCK have merit, as compared with soluble sources in the following crop situations: (1) forage and turf crops; (2) long-term tropical crops (sugar cane and pineapples); (3) citrus; (4) forestry and forest nurseries; (5) areas where leaching may be a problem; (6) fall and winter application where this practice is not recommended for soluble sources; (7) rice (modification of the SCU process may be required to increase the rate of dissolution in flooded soil); (8) any other crop situation where controlled-release of N or K may be beneficial.

for optimum early crop growth in a very P-deficient soil. This initial yield reduction caused by slow dissolution of SCP was not compensated for in later clippings, resulting in less total yield from SCP. Similar results have been reported by Terman and Allen (1970) for rice. Tracer-labeled concentrated superphosphate applied 6–9 weeks after crop establishment was readily assimilated, but uptake of late-applied P was not reflected in yield response.

EXPERIMENT 3. Cumulative uptake of K by three crops of corn, each of 6 weeks duration, is shown in Figure 5. At both rates of application, total uptake of K was greater from KCl than from SCK, which suggests incomplete dissolution of SCK in 18 weeks. As regards individual crops, approximately 70% of the total uptake of K by three crops was assimilated by crop 1 from KCl, as compared to 40% from SCK. Thus, uptake of K from SCK was relatively uniform throughout the cropping sequence, while uptake from KCl was excessive in crop 1, particularly at the higher rate of application.

Cumulative yield curves are shown in Figure 6. At the lower rate of application, yield and uptake curves are almost identical, which indicates that the supply of K limited plant

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