SYMPOSIUM ON CONTROLLED-RELEASE FERTILIZERS

Introduction

A fertilizer which will release its nutrients, particularly nitrogen, at the rate needed by growing plants seems a worthwhile objective from many points of view. Any of us who has ever got a burned strip on his lawn and any farmer who has not been able to get fertilizer to a growing crop when it needs it, as well as the agronomist trying to match plant uptake and fertilizer release curves, have all keenly felt the need for such a product.

Nature makes a fairly successful attempt at creating such a fertilizer by immobilization of soluble nitrogen and gradual release of the combined nitrogen, but this release is too slow and incomplete for most purposes. The natural organics come closer to the objective but have serious limitations. The development of a synthetic controlled-release nitrogen fertilizer has been the object of agricultural and chemical research for over 50 years. Solutions which could be used to generate insoluble nitrogen have been commercially available for over 30 years. The commercial solid ureaforms, carefully produced to meet rigid specifications, have also been available since the mid-1950's. It has been an active field of research with a variety of urea-aldehyde condensates and various coated fertilizers being reported since the introduction of the ureaforms.

The progress in this field has been well reported to the Division of Fertilizer and Soil Chemistry in the past, both in individual papers and groups of papers. Although this is an active field of research, holding a symposium on controlled-release fertilizers at this time is justified more by a need to evaluate our position than to report strikingly new developments. Our objective in this symposium is thus to see where we are, to see how far we have come, and to attempt to define obstacles still to be overcome. It is appropriate that we begin our symposium with a review paper by Dr. Lunt, an outstanding researcher in the field, and that subsequent papers concentrate on uses of the various types of products.

It is interesting to point out that in the group of five papers in the symposium we have only two speakers who are members of the American Chemical Society, one chemist and one chemical engineer; the other speakers include a biologist, a horticulturist, and an agronomist. This is very much as it should be; it clearly emphasizes the multidisciplinary nature of agricultural research. We chemists are happy to have these visitors; we have much to learn from them and look forward to similar joint research meetings in the future.

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Controlled-Release Fertilizers: Achievements and Potential

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Techniques for achieving controlled-release fertilizers are reviewed. These fertilizers are used mostly in turfgrass, ornamentals, and for other specialty situations. Use for rice and as a starter fertilizer for tree crops also looks promising. Data indicate that controlled-release fertilizers often provide greater efficiency, reduce labor requirements, reduce burning hazard, and improve crop performance. Concern over the introduction of nitrates into streams and lakes will require greater attention to efficient utilization of applied nitrogen. Although denitrification generally keeps nitrate contamination of streams, from fertilizer, at low levels, some studies show 50% or more of applied fertilizer nitrogen appearing in the drainage water. In view of the complexity and importance of pollution problems from fertilizers, which are briefly reviewed, more research on the effectiveness of controlled-release fertilizers, as contrasted to conventional materials in minimizing these problems, is needed.

Research on the first commercially successful, synthetically produced, controlled-release fertilizer was done about 25 years ago. The object of this research, ureaformaldehyde (UF), has been the most widely used specialty fertilizer. The market for UF nitrogen runs to several tens of thousands of tons, compared to about 7 million tons of soluble nitrogen sold for fertilizers, or not more than about 1% of the market. Thus, while the potential of controlled-release fertilizers is interesting, their use is still limited.

Controlled availability fertilizers in use are, in addition to ureaformaldehyde, crotonylidene diurea, 1,1-diureido isobutane (IBDU), metal ammonium phosphates, trace element glass frits, and coated soluble nitrogen sources. Various other materials such as oxamide have been shown to have desirable, slow-release characteristics. The basic approaches

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used to achieve controlled release are: limited solubility of compounds; use of nitrogenous compounds only slowly mineralized by microbial action; membrane-regulated diffusion from soluble sources; and use of materials based on cation or anion exchange resins. In addition, a number of compounds have been introduced which enzymatically retard the oxidation of ammonium to nitrite and nitrate and thus retard the leaching of nitrogen.

Because of their higher cost, the controlled-release fertilizers are being used primarily in nonfarm markets, *i.e.*, professionally maintained turf such as golf courses and parks, home grounds, and in the floriculture and nursery fields. Controlled-release fertilizers have earned an enviable reputation for safety and dependability in these high-value markets. Expansion of controlled-release fertilizers in this area is taking place, but significant expansion in the use of controlled-release fertilizers is dependent upon the development of lower-cost materials having management advantages in larger use crops. Of slow-release fertilizers currently under development, sulfur-coated urea may be the most economically attractive. This paper will mainly consider potentials of controlled-release applications with larger acreage crops.

Management advantages of controlled-release fertilizers are usually considered to be reduction in the frequency of application, reduction of injury hazard from large applications, greater utilization efficiency where leaching losses are normally high, or other crop management or convenience advantages. To what extent have these expectations been achieved and what potential remains to be exploited?

EFFICIENCY OF NITROGEN UTILIZATION AND POLLUTION

For economic reasons, the efficiency of use of nitrogen fertilizers has long been of interest. However, agronomists and fertilizer users alike have understandably focused attention on maximum economic return for dollar invested. With declining costs for nitrogen, the question of efficient recovery of nitrogen has also been a declining issue. The objective has been to fertilize until the value of expected yield increase no longer compensates for the cost of the last increment of fertilizer. Efficiency of recovery declines with heavy fertilization. Public concern regarding possible fertilizer contributions to pollution of streams and lakes will require more careful appraisal of fertilizer management practices and it is timely to ask if controlled-release fertilizers provide a means of reducing fertilizer contributions to pollution. Space permits only the briefest comments on these complex problems.

Recovery of fertilizer nitrogen by cultivated crops often represents only about $^1/_3$ to $^1/_2$ of that applied. In pastures, recovery typically is in the range of 70 to 100% (Allison, 1955; Cooke, 1964). Tracer techniques, ^{15}N in the case of nitrogen, are required to distinguish recovery from fertilizer sources or from soil nitrogen. Field studies using ^{15}N, because of their cost, have had limited use. Illustrative of the data obtained is that of Owens (1960), who used ^{15}N in a 2-year lysimeter study with corn. He showed 15 to 25% recovery in stover and grain from 150 lb of nitrogen from ammonium nitrate per acre. Leaching losses were 5 to 20%; 38% remained in the soil; and 33% was not recovered and was presumed lost by denitrification. Pollution concern is focused on the fate of nitrogen which is leached below the root zone of crops. Fortunately, from the pollution point of view, nitrates which reach the water table where reducing conditions prevail are fairly effectively reduced by microbial action and lost in gaseous form as N_2O and N_2. In the review on denitrification by Broadbent and Clark (1965), they summarized a number of greenhouse studies using ^{15}N, which showed percentage nitrogen losses ranging from 1 to 40. Several field studies cited showed denitrification losses in excess of 50%.

Overall, it appears that fertilizer contribution to pollution is small, but numerous special situations may be important. The review of lysimeter work done by Allison (1955) brought out that leaching losses of nitrogen were substantial, often exceeding $^1/_3$ of that applied, where heavy nitrogen applications were made, where soils were highly permeable, and where nonpasture cropping was used. Lysimeter data would tend to overestimate the amount of nitrogen which would ultimately appear in streams and lakes because of recovery of deeply distributed nitrate in some cropping systems and because denitrification under field drainage conditions may exceed that measured in lysimeters. Except in many acid soils, ammoniacal forms of nitrogen are normally rapidly converted to nitrate in well-aerated soils. As mentioned above, nitrate nitrogen is subject to denitrification in anaerobic environments. These losses also occur to some extent in environments generally considered aerobic (Meiklejohn, 1940), particularly where easily decomposable organic compounds are present. A study of nitrate levels covering a 30-year period, in the upper Rio Grande, which receives drainage waters from three irrigated sections of the valley, showed no increase in nitrate burden of the stream computed as metric tons per year (Bower and Wilcox, 1969). Actual concentrations of nitrate in drainage water remained in narrow limits below 3 ppm of nitrogen. It was estimated that during this 30-year period, nitrogen fertilizer usage increased by 35- to 100-fold. It was presumed that deeply percolating nitrate is lost by denitrification. Meek *et al.* (1969), in laboratory studies, found large amounts of denitrification with or without added organic matter under very wet conditions where the redox potential dropped to 300 mV or below. They further computed that nitrogen appearing in the effluent from drainage tiles (1.2 ppm of NO_3^-–N) represented about 1.5% of the added fertilizer nitrogen to cotton. These studies were conducted in the Imperial Valley, Calif., on a silty clay loam. On the other hand, a study by Johnson *et al.* (1965) measured the nitrogen content from drainage tile in the San Joaquin Valley from various cropping programs and found very large variations in the amount of nitrogen in the drainage water. In one system, drainage nitrogen represented more than 50% of the fertilizer applied. In a second system, drainage nitrogen losses were about 40% of applied nitrogen. From a third system, about 5% of the applied nitrogen appeared in the drainage effluent. These investigators concluded that smaller or more frequent fertilizer applications, or the use of controlled-release fertilizers, would reduce these losses. For a collection of abstracts dealing with the effects of fertilizers on water quality, see the publication compiled by the National Fertilizer Development Center (National Fertilizer Development Center, TVA, Muscle Shoals, Ala., 1969).

In summary, a considerable body of data indicate that, in general, fertilizers make a small contribution to the nitrate contamination of streams. As indicated in some of the work cited above, important exceptions may exist to this generality. More quantitative data are needed to identify the exceptional situations (Chem. Eng., 1969; Olsen *et al.*, 1970).

Do controlled-release fertilizers offer a means of minimizing fertilizer contributions to pollution? Olsen *et al.* (1970) conclude that limiting the rates of nitrogen fertilizer to approximately that required by the crop and careful management of cropping, irrigation, and fertilization practices will minimize losses of NO_3^-–N. Significant losses are most likely to occur on highly-permeable soils before the root system of a new planting is thoroughly established. While the answer to the above question will probably be determined by eonomic considerations, it would appear that the use of controlled-release fertilizers is particularly attractive as starter fertilizers where soil conditions make soluble fertilizers vulnerable to substantial leaching losses. Kofranek and Lunt (1962) and Lunt (1968) have demonstrated the safety and efficiency of membrane-coated fertilizers as starter fertilizers under these conditions.

As noted, the efficiency of plant recovery of fertilizer nitrogen has not been a matter of great concern by the industry. Concern for pollution problems may alter this thinking. Possible advantages in the efficiency of recovery would also compensate, to some degree, for higher costs of controlled-release fertilizers and, therefore, merit consideration. In this regard, Broadbent and Clark (1965) suggested that controlled-release fertilizers would have to reach a price which would not involve a premium of more than about 10 to 30% to warrant their use as a technique for reducing denitrification losses. Diamond and Mays (1970), in an economic evaluation of SCU, were optimistic on its potential.

In a comparison between sulfur-coated and uncoated urea, Lunt (1968) showed that yields and nitrogen recovery by corn were about as good from a single application of coated fertilizer as from three applications of urea in a sandy loam and a loam soil where irrigation practices were carefully managed to avoid large leaching losses. Under conditions of high leaching, or where single applications of urea were used, yield and nitrogen recovery from comparable applications of coated urea were superior. Tables I and II adapted from that study clearly point up the conditions where marked efficiency advantages over urea were achieved by the slow-release fertilizer, *i.e.*, where leaching losses were high and a large fraction of the urea was applied at the time of planting. Recovery percentage from sulfur-coated urea was much less dependent on leaching conditions than was the soluble source.

Mays and Terman (1969b) showed apparent nitrogen recovery from sulfur-coated urea (SCU) by Coastal bermuda grass to be consistently higher than from uncoated urea and ranged from 55 to 70% in a 3-year study. Recoveries were higher from single applications than from multiple applications of SCU at comparable nitrogen application rates. The apparent efficiency of recovery of ammonium nitrate was better than SCU only where very heavy rates were used with two or four applications. These same authors, Mays and Terman (1969a), found lower apparent recoveries of nitrogen from SCU than from various other soluble nitrogen sources by *Alta fescue* when single applications were compared. Annual yields were the same, however. Cropping data indicated nitrogen-left residual in the soil was greater where SCU had been used than it was from soluble sources. This was in spite of the fact that granules do not persist past the first year. Sulfur coating also apparently reduced the volatilization loss of ammonia from surface applied urea (Terman and Hunt, 1964). Reduction of luxury consumption of potassium by plants from controlled-release sources is also to be expected.

Two studies have attempted to account for all of the nitrogen from ureaformaldehyde. Brown and Volk (1966) using ^{15}N accounted for 90% of applied N after 8 months of cropping. About 58% had been recovered by the crop.

Table I

Nitrogen source	Apparent % recovery of fertilizer N[a]	
	Low leaching	High leaching
Sulfur-coated urea	67	61
Urea	71	47

[a] Apparent percentage recovery of fertilizer nitrogen by corn (average of three fertilizer rates). Coated urea was applied all at time of planting; urea in three applications. Low leaching plots received 22 in. of water; high leaching plots received 40 in. (from Lunt, 1968).

Table II

Nitrogen source	Apparent % recovery of fertilizer N[a]	
	Low leaching	High leaching
Sulfur-coated urea	79	68
Urea	32	6

[a] Apparent percentage recovery of fertilizer nitrogen by corn when 50 lb per acre of N was applied at time of planting. Low leaching plots received 22 in. of water; high leaching plots received 40 in. (from Lunt, 1968).

Kaempffe (1966) accounted for 97% of applied UF in a 3-month study. In this case, 48% had been recovered by the plant. The writer is not aware of studies which permit a direct comparison of losses resulting from denitrification from soluble and controlled-release fertilizers under comparable conditions. However, if controlled-release fertilizers can minimize NO_3 leaching past the root zone, denitrification losses should be reduced.

ADVANTAGES OF FREQUENCY OF APPLICATION

The advantages of reduced frequency of application and reduced injury hazard from large applications, which are so important in turfgrass culture, for home grounds use and ornamental horticulture, have not appeared to be sufficiently attractive to warrant their use in the major field crops. One practical problem merits consideration. One of the first problems in soil fertility studied over a century ago by Thomas Way involved the feasibility of fall application of fertilizer instead of spring application. Fall application may provide important advantages to the farmer. Practices in this country vary. In the U.S., Midwest experience shows that ammonium forms of nitrogen can be fall-applied with only a 3 or 4% penalty to corn yields on well-drained, silty, or clayey soils after the soil temperature at the 4-in. depth falls below 50° F (Walsh, 1970). In the Northeast and South, fall fertilization is frequently not advisable. A low-cost, controlled-release fertilizer which extended the feasibility of fall application would be a welcome tool for the agronomist.

In corn production, the trend toward narrower rows and higher plant populations makes the side-dress season shorter. This renders a long-lasting fertilizer more attractive, particularly on sandy soils.

Several crops have cultural characteristics which make single applications of fertilizer desirable or necessary. Strawberries are often grown on plastic sheets to keep the fruit off the ground and reduce spoilage. Fertilization after installation of the plastic is difficult. Voth *et al.* (1963) demonstrated the advantage of long-lasting fertilizers for strawberry production.

Rice is a crop in which there is interest in single-application fertilizer procedures. Ammonium fertilizers are more effective on lowland rice because of denitrification of nitrate sources. In rice culture, ammonium accumulation in the top 6 in. of flooded soil begins during the first week and reaches a maximum concentration in about the first 6 weeks and then declines. This pattern does not coincide with the plant needs and usually requires supplemental fertilization for maximum yields. Ahmad and Whiteman (1969) obtained yield increases of about 2.5× that of $(NH_4)_2SO_4$ from coated $(NH_4)_2SO_4$. The long-lasting fertilizers substantially reduced the response of a top-dressing 35 days after transplanting.

There has been sustained interest in the use of slow-release fertilizers in forestry, orchards, and for other perennial plants. Attoe and colleagues (1970) have approached membrane control from a unique angle. They have shown that perforated polyethylene capsules, or packets, can be designed which appear to be capable of effectively supplying fertilizers for up to 6 years. Sizeable responses from various trees were obtained. White (1963) and White and Boyd (1965) found that this method of fertilization gave improved growth and survival of pine and spruce seedlings in greenhouse and field studies. Exceptionally long-lasting fertilizer techniques would be interesting in forestry, and where repeated fertilizer application is expensive or difficult. Freeway plantings are often made in very poor soil material and, while maximum growth is not a consideration, establishment and rapid cover are important. "Single-shot" fertilizer packets in these applications would be useful.

CROP MANAGEMENT AND CONVENIENCE ADVANTAGES

Controlled-release fertilizers have been accepted in the production of exceptionally high-value crops for a variety of reasons. Highly dependable, safe, and optimal nutritional management programs for potted plants and other ornamental plants is sometimes claimed (Kofranek and Lunt, 1962). Hasek and Sciaroni (1970) found membrane-coated fertilizer (osmocote) formulations to more easily achieve optimum response in potted Ace lilies than liquid fertilizer programs. Prasad and Woods (1969) found single applications of membrane-coated fertilizer, SCU, or IBDU to be approximately as good as a liquid feed program every other day for a 14-week period in supplying N to tomatoes.

In turfgrass culture, high production is not usually an objective and is often a disadvantage. The objective is more often steady growth and good color. Ureaformaldehyde has been most effective in reducing large flushes of growth (Kaempffe and Lunt, 1967; Moberg *et al.*, 1970). About a third of the nitrogen in typical UF fertilizers is almost as available as ammonium nitrate; another third is much less slowly available; and a final fraction is still slower. Kaempffe and Lunt (1967) have estimated the mineralization of the latter fraction at about 10% per year or about five times as fast as nitrogen from native organic matter. As the amount of this fraction builds up in the soil, it is to be expected that sustained, uniform growth would be more easily achieved.

The advantage of low-burn hazard fertilizers for home grounds use is important where inexperienced users may be involved. The slow-release fertilizers have this advantage. Maximum safe application rates will vary, depending on the material, but the margin of safety is often impressive. Lunt and Clark (1969), for example, showed that IBDU could be safely incorporated in soils at rates of 32 lb of nitrogen per 1000 ft^2. Appropriate formulations of various materials make once-a-year fertilizer applications possible.

SUMMARY

In summary, a considerable amount of experience and research has shown that controlled-release fertilizers are often more efficient, have low plant injury hazard, and offer important convenience advantages. They has been largely confined to specialty, nonfarm applications. The prospect of lower-cost materials may extend their use into the farm market, where they could have a significant impact on management practices.

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