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Selenium Deficiency in Soils and Its Effect on Animal Health

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ABSTRACT

Selenium in minute quantities has been shown to be a dietary essential for animal life, and soil-plant-animal relations have been identified in the distribution of the element. In some cases, soils are frankly deficient in selenium—most particularly those derived from igneous rocks, and the deficiency in surface layers may be aggravated by intensive irrigation. Alternatively, soil selenium may exist in a form that is either unavailable to plants or absorbed by them with difficulty. Representative of such a form is the highly insoluble ferric oxide-selenite complex which frequently occurs in high-moisture, acid soils. Uptake of selenium by plants may also be inhibited by presence of interfering substances in the soil, such as sulphur, or it may be enhanced by liming. Analytical surveys have revealed also that considerable variation exists among plant species in their abilities to take up and retain selenium from the soil. Legumes have been consistently implicated as forages conducive to white muscle disease, a selenium-responsive myopathy, and New Zealand observations have shown white clover (*Trifolium repens* L.) to contain significantly lower levels of selenium than grasses, and particularly a native grass, browntop (*Agrostis tenuis* Sibth.). In addition to the differences in absolute selenium uptake, it has been suggested that some plants, and again legumes are suspect, may contain organic inhibitors of selenium utilization by livestock. Some experiments have investigated the effectiveness of additions of selenium to the soil in overcoming selenium deficiency among farm animals. Protection for 2 yrs has been achieved by this technique; however, the various factors influencing the soil-plant-animal relations of selenium direct caution in its application.

INTRODUCTION

In 1965, Douglas Frost engagingly documented the changes that have recently taken place in the understanding of selenium's effects upon animal life: "Just when the detectives had caught up with selenium in all its rascality—impugned as a carcinogen, and about the only element sly enough to be taken up by plants at high enough levels to poison animals—selenium played its trump card. It became an essential nutrient," (Frost, 1965). The knowledge of selenium's essential status was accumulated stepwise. First, Schwarz and Foltz (1957) demonstrated that selenium would protect rats fed Torula yeast diets from necrotic liver degeneration, following which it was found similarly protective against exudative diathesis in poultry (Patterson and others, 1957) and against white muscle disease (WMD) in young ruminants (Muth and others, 1958). These isolated instances led to the recognition of several selenium-responsive diseases, which affected a number of different animal species in widely separated parts of the world (Sharman, 1960). Finally, by the use of carefully controlled experimental diets, uncomplicated selenium deficiency was produced in Japanese quail (Thompson and Scott, 1968) and in rats (McCoy and Weswig, 1969).

In the course of these investigations, and particularly those relating to field cases of selenium-responsive disease, it became evident that a chain of relationships existed through the soil-plant-animal cycle involving selenium. Coupled with earlier knowledge of selenium toxicity (Trelease and Beath, 1949), it appeared that these relationships might operate across a very broad spectrum of selenium levels. Presence of high levels of selenium in certain soils had been known for some time and were catalogued by Lakin, (1961). The identi-

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fication of such seleniferous soils was aided by the discovery (Beath and others, 1934) that certain indicator plants, which had the ability to accumulate high levels of the element, grew in high-selenium areas. These plants were shown to be involved in selenosis of animals (Beath and others, 1932). The other end of the scale, now recognized as selenium deficiency, has been less completely charted. In a large part this has been due to the analytical difficulties involved in coping with what Schwarz (1961) has called the "elusive qualities of the element," although some significant advances have occurred in this country (Kubota and others, 1967). The soil-plant-animal relations in selenium deficiency are less clear, and have caused Allaway (1968a) to remark, "In few, if any, of these (deficiency) cases was the occurrence of the problem predicted in advance on the basis of the geology of these areas." On the other hand, reasonably direct relationships have been described between levels of selenium in plants and incidence of selenium deficiency (WMD) in animals (Allaway and Hodgson, 1964). Thus, involvement of interfering factors in the transmission of low levels of selenium from the soil, through plants to animals was implied, and these factors form the basis for much of this paper.

SIGNS OF SELENIUM DEFICIENCY

There are two major signs of selenium deficiency in animals: liver necrosis, which has been repeatedly demonstrated under controlled experimental conditions in rats and mice, and a similar condition, called hepatosis dietetica, in swine, and a myopathy which frequently occurs under field conditions in young ruminants and in poultry. The muscle damage may be accompanied by calcification, as in WMD of calves and lambs or by exudation of cellular fluids into extracellular space, as in exudative diathesis of poultry. Frequently associated with such specific signs of selenium deficiency are poor growth of hair or feathers, and general depression of rate of body growth. These relationships suggest the association of selenium with the protein moieties of the tissues of animals, and such has proven to be the case (Ganther, 1965). The frequency of occurrence of WMD in cattle and sheep in certain areas provides at least circumstantial evidence for a soil-plant-animal relationship, since these animals, probably more than most others, are restricted in their diets to locally grown forages.

SELENIUM-DEFICIENT SOILS

It seems possible that some, at least, of the cases of selenium deficiency in livestock owe their origin to an uncomplicated deficiency of the element in the soils on which feeds for the animals were grown. Anyone who has suffered through the difficulties of retaining minute amounts of selenium through destructive analytical procedures is well aware of the element's volatility in the presence of heat. Several investigators have noted the escape of large quantities of sulphur, and lesser quantities of selenium, from volcanic systems in the form of volatile gases (*see* Lakin and Davidson, 1967). These authors state, ". . . the soils derived from igneous rocks are most likely to be uniformly deficient in selenium." It is noteworthy that much of the soil in the eastern parts of Washington and Oregon and in northern California, which is described as the source of "very low" selenium levels in crops (Kubota and others, 1967; Carter and others, 1968) is of fairly recent, volcanic origin. Much of this area is presently subject to fairly strong prevailing winds from the Pacific coast, which, if they occurred historically, might have dispersed the selenium volatilized in the deposition of soil parent material to the eastward. The residual volcanic soil roughly coincides with areas where WMD is a fairly frequent and serious occurrence (Muth and Allaway, 1963).

The deficiency of soil selenium may be aggravated by irrigation, and again, it is pertinent that one of the areas of most severe incidence of WMD, near Madras, Oregon, has been subjected to intensive irrigation in recent years. Although specific data from this area are not available, there have been studies made elsewhere on the effects of leaching upon soil selenium. Williams and Byers (1935) showed in studies of the alkaline, seleniferous soils of the Gunnison and Colorado river basins that, while salts forming on the walls of drainage ditches in Mesa and Montrose Counties, Colorado, contained from 16 to 260 ppm selenium, the soils irrigated by the ditches rarely contained over 2 ppm. Fleming and Walsh (1957) also demonstrated effects of soil leaching upon selenium content by showing that Irish soils high on valley walls contained minimal levels of selenium (0.5 to 1.2 ppm); lower down they contained more (4.1 to 6.2 ppm) and on the poorly drained valley floor they contained surprising accumulations (63.4 to 225 ppm). Ravikovitch and Margolin (1957) provided further evidence of depletion of topsoil of selenium by continuous cropping when they demonstrated that alfalfa planted on virgin soil in Israel contained up to 44 ppm of selenium in the first crop year, but barely detectable amounts 3 yrs later. Investigations in Western Australia also implicated leaching losses in the low-selenium soil picture, in demonstrating an inverse relationship between soil selenium content and mean annual rainfall, although complications due to soil differences and length of time the land had been cropped were recognized (Gardiner and Gorman, 1963).

It seems reasonable to assume that, in addition to soils that are frankly deficient in selenium due to losses of the element either in the processes of their formation, or subsequently, others may exist in which selenium is present, but in a form unavailable to plant life. Elemental selenium, for example, can be found in soils treated with Na_2SeO_3. This form is not readily available to plants; nor surprisingly, is it easily oxidized to forms that are available. The extent to which elemental selenium is a naturally occurring soil constituent, however, is not well known. Where soil parent material weathers under humid conditions to form acid soils, its content of selenium is inclined to form highly insoluble ferric oxide-selenite complexes, which are also unusable by plants. Plants which contain insufficient selenium to meet the nutritional requirements of animals characteristically grow on acid soils formed from low-selenium rocks (Allaway, 1968a).

INTERFERING FACTORS IN SOILS

Quite early in the investigation of WMD in Oregon, it was observed that incidence of the disease was sometimes increased following the application of gypsum, $CaSO_4 \cdot 2H_2O$, to the soils on which forage for the animals' feed was grown (Muth, 1955). Antagonism between selenium and sulphur has been known for many years, and has been interpreted by Leggett and Epstein (1956), on the basis of results from studies of the kinetics of sulphate absorption by barley roots, as a competition between the two ions for an absorption site.

Davies and Watkinson (1966) compared the content of selenium in plants fertilized with sodium selenite alone, or mixed with superphosphate on a peat soil base, and found it lower where the superphosphate was included (0.57 *versus* 0.43 ppm, respectively). They attributed the lower content to preferential stimulation of the plant growth by the superphosphate-sulphur, rather than to competitive absorption between sulphate and selenite by the plants. There have been other indications, though, where sulphur-selenium competition does seem to have been directly involved. The uptake of selenium by winter wheat was decreased from 110 ppm to 2 ppm by application of gypsum or of elemental sulphur (Hurd-Karrer, 1935; Hurd-Karrer and Kennedy, 1936). Shrift (1961) reporting on studies conducted with *Chlorella vulgaris* suggested that at any one exogenous level of a selenium compound the concentration of cellular selenium falls with an increase of exogenous sulphur. Sulphate interference with selenium appears to operate at the soil-plant level rather than at the plant-animal level in the food chain, since, in Oregon studies, the supplementation of WMD-causative diets with sulphate did not increase the over-all incidence of the disease (Whanger and others, 1969). It has been suggested, however, that the very limited absorption of sulphate from the intestinal tract of animals may be an important deterrent to effective competition between sulphate and selenium in the animal (Ganther and Baumann, 1962).

Some circumstantial evidence has been provided that other inorganic elements may inhibit the uptake of selenium, from soil, by plants. Cannon (1969), for example, has reviewed the close relations that exist among uranium, molybdenum, selenium, and vanadium in certain soils. Taboury and Coudray-Viau (1939) presented data indicating that the concentrations of iron, manganese, magnesium, and lithium were higher in normal plants than in seleniferous plants. Of these, the relationship between iron and selenium has received more critical attention than the others. Allaway (1968b) has summarized this situation succinctly: "Selenites are very strongly bound by hydrous oxides of iron, and these iron oxide-selenite compounds or complexes are very insoluble from about *p*H 4 to *p*H 8.5."

Just as presence of certain ions in the soil inhibits the uptake of selenium by plants, the presence or effects of others may enhance it. The association of low-selenium forage with acid soils, previously mentioned, suggests a possible beneficial effect from liming certain selenium-deficient soils. The studies of Cary and others (1967) confirm that liming certain selenium-deficient soils will slightly increase the uptake of selenium by plants, but it is doubtful that this increased plant-selenium concentration would be significant in animal nutrition.

VARIATIONS IN UPTAKE OF SOIL-SELENIUM BY PLANTS

The soil-plant-animal cycle for selenium is further complicated by variations in the abilities of different plants to remove selenium from the soil and incorporate it in their tissues. The most dramatic variants are the selenium-accumulating plants, and Moxon and others (1950) have reported that *Stanleya pinnata* concentrated 2,380 ppm of selenium as compared with only 6.8 ppm in *Artemesia canadensis* grown in close proximity (an area of about 4 sq rods) on the same geological formation. There is some evidence that variation may also occur at the other end of the scale, and that certain forage plants may be more conducive to selenium-responsive diseases of animals than others, when grown on soils of low-selenium content or availability.

It has been observed in Oregon that field cases of WMD occur more frequently when legumes have been fed than grasses (Muth, 1963), and alfalfa has been commonly chosen as the basis for low-selenium experimental diets. This situation may reflect the choice of alfalfa as a means of improving irrigated rangeland, however, rather than inefficiency of selenium uptake by alfalfa. Beeson (1961) noted that little evidence existed which would suggest that alfalfa could absorb large quantities of selenium; however, extensive data assembled by Hamilton and Beath (1963) did not show alfalfa to be less efficient than many other plants, including range grasses and forbs, in removing selenium from soils containing measured amounts of either inorganic or organic selenium compounds. Roughan (1965) has observed that there is little evidence to suggest that, under natural conditions, legumes will take up less selenium from the soil than grasses. Alfalfa generally produces more forage than grasses, and its selenium content may be diluted by this greater amount of plant material.

In New Zealand, the central pumice plateau of the North Island is the site of extensive WMD and "ill-thrift" among lambs, both of which respond to administration of selenium. In this setting, Davies and Watkinson (1966) studied comparative efficiencies of selenium uptake by several indigenous species of pasture plants. Marked differences occurred between plant species in selenium uptake. Among the species studied, browntop (*Agrostis tenuis* Sibth.) consistently showed the highest concentration and white clover (*Trifolium repens* L.) the lowest concentration, with orchard grass (*Dactylis glomerata* L.) and perennial ryegrass (*Lolium perenne* L.) intermediate. The 3 grasses average selenium uptakes two to four times greater than that of the white clover. It is noteworthy that the highest incidences of selenium-responsive diseases in New Zealand livestock are associated with improved pastures, particularly lush swards rich in clover (Cousins and Cairney, 1961), and seldom with unimproved "browntop country." In contrast, little difference in selenium-75 uptake by wheat, ryegrass, red clover, and white clover was recorded by Peterson and Butler (1962). However, their studies were conducted in highly purified nutrient solutions, rather than in soil media.

INTERFERING FACTORS IN ANIMALS

There has been some evidence for years now that certain stress factors, either physical or chemical in nature, may aggravate or precipitate selenium deficiency. Muth (1955) observed in Oregon that outbreaks of WMD were apt to occur or to increase in intensity when periods of warm sunshine interspersed the usually cold weather at calving and lambing time. Similarly, Gardiner (1962) reported from Western Australia that deaths or sudden lameness were especially frequent when sheep were driven and excited during some operation, such as shearing, dipping, drenching, or vaccinating. This situation was examined experimentally in this country by Young and Keeler (1962), who tied up one leg of lambs born to ewes fed a low-selenium diet and found that the lesions of WMD appeared in the opposite functional limb only. The metabolism of selenium appears to be affected to some extent by the metabolism of vitamin E, and at least in some cases, WMD has occurred with concurrent selenium and vitamin E deficiencies. Blaxter's observations showed clearly that chemical stress could be imposed on animals that would cause myopathy by feeding pro-oxidants, such as highly unsaturated fish oils, which would destroy much of the dietary tocopherol (Blaxter and others, 1953).

Also, it would seem logical that, if selenium supplies through the soil to forage plants are marginal, increased competition of animals for the limited selenium available might increase incidence of deficiencies. Gardiner (1969) has described such a situation in Western Australia, where stocking rates of sheep on pasture almost doubled over the decade 1957 through 1967. Similar intensification is taking place in this country, and in many other parts of the world. In addition to the competitive aspect already alluded to, this situation may be intensified by the cycling of selenium through sheep. In this process, microbial activity in the rumen has been shown to change organic forms of selenium, ingested in the plants to insoluble, inorganic forms returned to the soil in manure (Peterson and Spedding, 1963).

IMPROVEMENT OF FORAGE-SELENIUM LEVELS FROM LOW-SELENIUM SOILS

One of the strategies available for the prevention and control of WMD and other selenium-responsive diseases among foraging animals is the amendment of low-selenium soils with the deficient element. Grant (1965), in New Zealand, demonstrated the possibility of raising the selenium content of pasture forage in a selenium-deficient area by top-dressing the pasture with Na_2SeO_3 at rates up to 1 oz of actual selenium per acre. Selenate proved more efficient initially in raising forage selenium levels, but these elevated levels did not persist appreciably longer than those achieved with an equivalent amount of the cheaper, and more readily available, selenite. Elemental selenium was ineffective in increasing levels of forage selenium.

Grant's experiments were conducted on soils which were considered normal, or at worst only marginally deficient in selenium. Allaway and others (1966) studied the effects of selenium amendment of a frankly deficient soil near Madras, Oregon. A further point of difference was that the selenium, as Na_2SeO_3, was injected into the soil, in water solution, to a depth of about 10 cm, with a liquid fertilizer applicator. The rate of application was 1 ppm Se in the surface soil. Sufficient selenium was conveyed to alfalfa forage at this application rate to prevent WMD in lambs for up to 2 yrs postapplication. On the basis of five cuttings of alfalfa harvested, it was calculated that only 2 percent of the selenium applied to the soil had been removed with the crops. Unfortunately, further data on residual effects were unavailable.

Davies and Watkinson (1966) mixed sodium selenite with either monocalcium phosphate or superphosphate and applied it to pastures on a considerable range of soil types. They showed that the forage-selenium levels were higher following the monocalcium phosphate-mix than the superphosphate-mix, and that initial uptake of selenium was higher from peat soils than from mineral soils. This elevated uptake did not persist, however, and at about 300 days the selenium level in forage grown on peat had fallen below that considered adequate for animal health. Practical application of selenium to deficient soils is dependent upon the ability to avoid toxic levels in forage, as well as to achieve levels which are nutritionally adequate. Some encouragement on the former point has been provided by Ehlig and others (1968) who noted that differences in accumulation of selenium by "non-accumulator" forage plants grown on properly supplemented, low-selenium soils were small.

SUMMARY

This paper has attempted to document the soil-plant-animal cycle for selenium as it operates at "physiological" or "deficient" levels of the element. Pursuing the relationship in reverse order, there is a great, and growing, body of evidence of the existence of selenium-responsive diseases of livestock which occur all over the world. It seems probable, although by no means clear at this point, that the susceptibility of animals to such disease may be modified by factors other than selenium, notably vitamin E.

Consideration of the soil-plant relationships reveals that under certain conditions soils may be expected to form which are selenium-deficient. Such deficiency may be expected particularly in acid soils derived from igneous parent materials, and it may be aggravated in some soils by excessive leaching caused by irrigation. Prediction of selenium-deficiency conditions for livestock from soil data is complicated by several factors, however. The availability of soil selenium is affected by the chemical form in which it exists, as well as by the presence or absence of certain interfering factors, such as sulphate. In addition, variances exist in the extent to which different plant species can absorb selenium from the soil at physiological levels or less. These variations

are much less spectacular than those which exist at the toxic end of the selenium spectrum, involving the so-called "accumulator" plants, but their effects may be no less damaging to animal health.

Finally, some means have been demonstrated for overcoming selenium deficiency by either pasture top-dressing or soil amendment. Available data indicate that, at best, soil treatment is an inefficient way of providing selenium in terms of the amounts required by animals. Moreover, the dangers of selenium toxicity, coupled with the variations in selenium availability and uptake from various kinds of soil by the many different species of forage plants, suggest caution in the use of these methods of alleviating selenium deficiencies among animals.

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