THESIS

ZINC IN POTATO PRODUCTION

Submitted by

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ABSTRACT

ZINC IN POTATO PRODUCTION

Zinc deficiencies have been reported from the states of Washington, Idaho, North Dakota and Texas. The deficiencies are reported to be localized in areas where the parent material of soil is low in zinc content or where the topsoil has been removed by landleveling or lost through erosion.

There is evidence that zinc plays an important role in the synthesis of tryptophane, an amino acid that is necessary for the formation of the growth hormone, auxin. Other data indicate that zinc is essential for the metabolic activities of some enzymes.

No difficulty has been reported in correcting the deficiency. Foliage and soil applications of zinc sulfate have given a yield response. Some workers indicate that a broadcast application and incorporation with a disc will produce a yield response where other methods will not.

Foliage symptoms and response to method of application seems to differ with varieties.

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INTRODUCTION

The potato (Solanum tuberosum) is still considered one of the staple foods that is consumed universally. The total volume consumed in the United States has increased from 180 million cwt. (hundred weight) to 200 million cwt., even though the per capita consumption has remained steady at 100-110 pounds for the last ten years. The total value of this crop over the past ten years has averaged $436,600,000.00 per year.

Through better production methods the yields per acre have increased from less than 75 cwt. in 1934 to 200 cwt. in 1964.

What part zinc will have in increasing the yield per acre is not yet fully known but any practice that will enable the producer to increase his production efficiency will be of value to the producer and to the ultimate consumer.

PURPOSE OF REPORT

The role of zinc in the growth of plants is highly complex. Until recently, very little was known about zinc and how it affected the growth of the potato plant.

The purpose of this report is to determine the extent of the zinc deficiency problem and its effect on potato production. Recorded symptoms, requirements, and the functions of zinc in potato production will be presented; and in addition, the sources of zinc and the factors that affect zinc availability to the plant will be discussed. Plant analysis, soil tests, and chemicals are the methods and materials which have been used to investigate the zinc deficiency problem. These will also be presented.

Research work dealing with potatoes and/or zinc will be reviewed in an attempt to establish the role of zinc in potato production.

IMPORTANCE OF THE ZINC DEFICIENCY PROBLEM

The first of the minor elements to be recognized as essential was iron. A French scientist, A. Gris, in 1844, described how chlorosis of some plants can be corrected by sprays of iron salts. It was after 1900 that the importance of zinc was recognized (26).

Callbeck (15) gives the following history of the discovery and recognition of the importance of zinc as a nutrient for plants.

> "In 1870, Raulin reported that the growth of the fungus, Aspergillis niger, was stimulated by the addition of zinc salts to the nutrient solution; in 1908, Javillier established the essential nature of zinc in the nutrition of chlorophyll-containing plants; and confirmations of his studies were published by Sommer and by Sommer and Lipman; who, however, presented no detailed discussion of the appearance of the plants without it. The symptoms of zinc deficiency in potato plants were studied by Schreven in extensive and carefully conducted water culture experiments by means of which he showed that potato plants deprived of the element were stunted and exhibited necrotic spots on the leaflets. Dostal reported that zinc increased considerably the growth of potato seedlings in solution cultures.
>
> "From a study of fourteen experiments with the use of sulphates of copper, manganese, and zinc in fertilizer mixtures for potatoes, Hester and Carolus reported that no significant increase in yield was produced. Yield data, reported by Morgan in Western Australia, indicates that no benefit was derived, as measured by yield, from the inclusion of zinc, or of certain other minor elements, in potato fertilizer mixtures."

In 1941, Maine (25) reported a slight response to an application of zinc sulfate on potatoes but it was not significant. No response was reported from Connecticut (12), South Carolina (2) where it was combined with a lime application, Nebraska (42), Iowa (33), and Nova Scotia (19).

Maine (63) reported some indication that zinc sulfate applied where potatoes were grown every year or frequently, gave some response. Significant increases were reported in the Red River Valley (34) with the use of such zinc bearing materials as Zerlate, Dithane Z-78, and Tri-Basic Nu-Z. Yield responses were also recorded in Delaware (27) using carbamate sprays and zinc with other minor elements (10).

The most significant results were achieved in Canada (Prince Edward Island, Manitoba, and British Columbia) in a cooperative trial in 1956. The practice of soaking seed pieces for two minutes in a 0.08 N solution of zinc sulfate produced significantly higher yields than zinc sulfate or acetate applied by drill applications. Slight increases were noted with the drill applied zinc but were not significant compared to the check (19).

A survey in the United States in 1961 by the Council on Fertilizer Application (4) and others (1) disclosed that 32 states have experienced zinc deficiency in at least one area. States of Washington, North Dakota, and Wisconsin reported zinc deficiency in potatoes.

Knowing the conditions which are conducive to zinc deficiency has increased the number of states reporting response from zinc. Texas (14) and Idaho (36) report that significant increases were obtained with an application of zinc. Better results were obtained where the zinc was broadcast and disced into the soil than where it was used in a band application (36).

Where response to zinc has been obtained, it has been primarily an increase in tuber size rather than an increase in number of tubers per plant. Iritani (36) found no change in specific gravity in Idaho.

Reports indicate that the deficiency is not a general problem, but localized.

Observations made on other crops certainly point out the potential of zinc for potatoes. As much as 30% increase in yield has been obtained on corn without deficiency symptoms visible (4). Furthermore, an acre of healthy oats contains only about one ounce of zinc, yet without this essential ounce, there would be no crop (1).

ZINC DEFICIENCY SYMPTOMS OF POTATOES

Conditions which alter zinc deficiency symptoms of plants have been shown to act in three ways: first, by directly influencing the concentration of zinc in the soil solution; second, by altering the absorption of zinc by plants; and third, by directly or indirectly altering the retention of zinc within the roots or other conductive tissue (66).

Visual

Potatoes grown in solution cultures without zinc have a slow growth rate and will be stunted. The top leaves assume a slightly vertical position, while the margins of some of the leaflets curl slightly upward. Leaves of deficient plants are small, upperinternodes short, and their stems are rigid (59).

There is every indication that a zinc deficiency will manifest different symptoms in different varieties. The following differences, however, were noted under different conditions and the varied symptoms may be due in some degree to these different environmental conditions.

McMurtrey (44) gives the following zinc deficiency symptoms on potatoes. Leaves with grayish brown to bronze irregular spots, usually on leaves halfway up the plant, but sometimes on older or younger leaves and finally on almost all leaves; with severe deficiency, stems and leaf petioles develop brown spots; plants short.

Symptoms observed on the Red Pontiac variety in North Dakota (24) were like those described by McMurtrey, but in addition the leaves were rolled inward and were dying.

On the Russet Burbank (Netted Gem) potato, a conspicuous stunting of leaves of the terminal growth occurs without the yellowing of leaf tissue and stunting of lower leaves (71). A complete description of the symptoms follows (56):

> "Affected potato plants are characterized by severe stunting and leaf malformation and by an indistinct bronzing or yellowing of the foliage, usually around the leaf margins. Leaf distortion is most pronounced on the youngest leaves, which are cupped upwards and rolled to such an extent that the terminal growth resembles the unfolding fronds of certain ferns. This symptom has suggested the term 'fern leaf' to describe the condition. Leaves on affected plants do not expand to normal size but become thickened and brittle. Leaf development behaves as though the marginal tissue ceases to expand, thus causing an S-shaped bending of the midrib, pleating of vascular strands, and puckering of the intercostal tissue."

A report indicates that symptoms on the Russet Burbank potato are more common and severe at earlier than at later stages of growth (71) and that once the "fern leaf" symptoms appear on the Russet

Burbank, the plant will decline rapidly and eventually die. Foliar applications of zinc are completely ineffective for correcting this deficiency on the Russet Burbank (6).

The "fern leaf" symptoms never seemed to appear on the White Rose variety in Washington (7).

Cytology

Zinc deficiency in plants causes several abnormalities in structure. These are (54):

> "The palisade cells of leaves from most affected plants are larger and are transversely divided, rather than columnar, as in normal leaves. Zinc deficiency, therefore, may lead to cell enlargement rather than cell differentiation. Other abnormalities may be a reduction in the number of chloroplasts, the absence of starch grains, the presence of oil droplets in the chloroplasts, the presence of calcium oxalate crystals, and the accumulation of phenolic materials in the leaves. These changes in chemical composition indicate that zinc is related to normal metabolism of carbon within plants.
>
> "The roots of zinc-deficient plants are also abnormal. Tomato roots may have a series of swellings, with whorls of root hairs near the root top. Secondary roots may develop later in them. Cell structure is also deranged; cells even in the meristematic, or actively growing, region may be enlarged, and an irregular arrangement with many air spaces may occur among the cells. Older tissue becomes necrotic and has flaky masses of exfoliated cells. Metabolic products of the root cells also are abnormal. Tannin, fats, and calcium oxalate crystals are present in abnormally large amounts. Starch is absent."

ZINC NUTRITION OF POTATOES

Until recently, very little has been known about the zinc requirements for the growth of the potato and less about how zinc functions within the plant. There are indications that very little zinc is required by the plants and that some plants either need less zinc than others or are able to obtain their needed supply more readily (59).

Absorption

Zinc is readily absorbed from dilute solutions. Workers have obtained marked responses in cotton growth from the addition of 0.001 p.p.m. of zinc to purified solution cultures (13), and only 0.1 p.p.m. of zinc was needed in solution for normal growth of pine seedlings (78).

This capacity of plants to secure needed amounts of zinc from such low concentrations probably accounts for the lack of difference in zinc uptake from various materials.

Zinc is probably assimilated principally as the divalent ion, Zn^{++}, with the possibility of some assimilation in such monovalent forms as $(ZnCl)^{+}$. It is doubtful that the pH of living roots would enable assimilation of measurable amounts of zincate ions which may occur under alkaline conditions (66).

Translocation Within Plants

One condition influencing the translocation of zinc within plants may be the amounts of other ions or compounds. Plants grown in solutions high in phosphate had zinc precipitated along the veins (66). Under high iron nutrition, zinc precipitation in conducting tissue was reduced, apparently because the concentration of soluble phosphate was reduced by precipitating with iron. Under conditions of low phosphate, zinc was distributed rather uniformly through leaves and was not markedly concentrated along the veins. Other workers (7) have reached similar conclusions, that applied phosphate has actually inhibited absorption or translocation, or both, of zinc to the aerial portion of the potato plant.

A related example of zinc fixation in plant tissues as a result of nutrition has been reported (49). Subterranean clover plants growing on soil low in zinc showed increased severity of zinc deficiency symptoms when the nitrogen supply was increased, regardless of the nitrogen source used. Under conditions of low zinc supply, the zinc concentration in roots was found to be positively correlated with the percentage of protein nitrogen. The zinc content of plant tops decreased with nitrogen application. The fixation was interpreted as resulting from formation of immobile zinc-protein complexes bringing about zinc retention in the roots under conditions of high nitrogen and low zinc. Later data (23) supports this concept in that 77 per cent of the zinc retained in roots of pea plants was in the insoluble residue, whereas 60 to 85 per cent of the zinc in the top parts was soluble in cold water.

Ozanne (50) has also found that light conditions may influence zinc absorption and translocation. Subterranean clover plants took up more zinc under long-day conditions than under short-day conditions, but a larger percentage of the absorbed ion was retained in the roots. The increased retention in the roots was attributed largely to increased root weights in relation to leaves. It appeared that under high light intensity growing leaves were able to utilize the zinc more efficiently than under medium light intensity.

In view of reports that phosphate, iron, and nitrogen nutrition and high light intensity influence the retention of zinc within plant tissue, it would be expected that data on zinc movement from one part of the plant to other parts would be variable (66).

Thorne (66) cites the work of Wood and Sibly who concluded that no zinc was translocated from leaves to other organs in an oat plant.

Deficiency Levels in Plants

In North Dakota (39) the zinc content of potato leaves showing no visible deficiency symptoms was measured and ranged from 13 to 87 p.p.m. on a dry matter basis. A wide variation occurred in every area sampled and was not related to a specific variety. It was postulated that plants containing less than 30 p.p.m. would show some response to foliar applications of zinc. Other data indicate that potato plants with leaf zinc content below 15 p.p.m. can be suspected of zinc deficiency (66), or that 10 p.p.m. of zinc in the total top at maturity is adequate for normal growth and a twenty ton yield (9).

Data are not sufficient to establish critical zinc levels for potatoes. No doubt the level at which response may occur varies somewhat in even the same crop variety, depending on other nutritional or environmental factors.

Work on other plants, such as cotton (13) and pine (78), has indicated a difference in response from different species. The difference in the variety Russet Burbank has been noted, and what different reactions might be seen in other potato varieties, remains to be seen.

There is a possibility that the phosphorus/zinc concentration ratio in critical tissues may be as important as the absolute concentration of these nutrients (7).

There is limited information available on the total mineral content of a potato plant. The potato tubers contain very little zinc as shown in Table 1 (22).

Table 1. Mineral content of a potato tuber.

Mineral	%	Mineral	%
Potassium	.496	Aluminum	.00097
Phosphorus	.053	Zinc	.00040
Chlorine	.035	Manganese	.00017
Sulfur	.029	Copper	.00016
Magnesium	.027	Nickel	Trace
Sodium	.024	Cobalt	Trace
Calcium	.013	Barium	Trace
Iron	.0011	Iodine	Trace

FUNCTION OF ZINC IN PLANTS

Auxin Relations

The leaves of zinc deficient tomato plants contained more reducing sugars, but slightly less sucrose and starch, than non-deficient plants. This was given as an indication that one of the essential enzyme systems failed or was blocked in the malnourished plants (51). Other workers (66) concluded that zinc plays a role in the production or functioning of several enzyme systems in the plant, but the interrelationships have not been clarified.

Retarded stem elongation, small narrow leaves and misshapen tomato fruit associated with zinc deficiency led to an investigation of the relations between the deficiency and auxin production. Conclusions reached were that the decrease in auxin precedes appearance of visible deficiency symptoms; the lack of zinc leads to excessive

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destruction (probably oxidation) of auxin, which in turn causes retardation of growth and abnormalities in correlative functions; and that zinc is not the principle requirement for the synthesis of auxin but for its maintenance in an active state (57, 65).

Later work (38, 67) confirmed and clarified the role of zinc in auxin relations to the plant. It was agreed that zinc deficient plants were lower in auxin content and further showed that the decrease in auxin applies to bound auxin as well as free auxin. Applying earlier work on Aspergillus niger that auxin is formed from tryptophan, the study was directed to finding the relation of tryptophan content to zinc deficiency. This work was summarized by stating that zinc is required directly for the synthesis of tryptophan and indirectly for the synthesis of auxins.

Zinc is associated with water relations in plants (54). High osmotic pressures resulting from zinc deficiency are due to reduced water uptake, which was restricted by the failure of cell walls to grow because of lack of auxin.

Tsui (68) states that it is a known fact that auxins play an important role in water absorption. The work with zinc deficient tomato plants showed a significant decrease in water content and retardation of growth compared to control plants. Two days after the addition of zinc to the deficient plants, the water content had increased and this was accompanied by an increase in growth. Tsui also cites the work of Showacre and DuBuy who concluded that the well known effect of auxin in bringing about cell elongation is due to auxin-enhanced water uptake.

There is every indication that different species or varieties will exhibit different responses to zinc deficiency. Work on two species of cotton (Gossypium L.) exhibited most striking differences on height (13). A similar response was shown with two species of pine (78), and in both instances the workers concluded that these results confirmed the hypothesis that zinc deficiency affected the auxin relation within the plant.

The observation that zinc deficiency does not develop so readily in mild sunlight as it does in bright sunlight may also show that it is associated with auxin activity. Light of high intensity and of short wave lengths inactivates auxin (50).

Enzymes

Zinc is a necessary component of several enzyme systems, which regulate various metabolic activities within plants. It is a part of the enzyme carbonic anhydrase, which regulates the equilibrium between carbon dioxide, water, and carbonic acid. Zinc also functions as a part of two enzymes, dehydropeptidase and glycylglycine dipeptidase, which have a part in specific aspects of protein metabolism (54).

ZINC TOXICITY OF PLANTS

Agriculturists were aware of the toxicity of zinc to plants before they knew it was essential. In a review of zinc deficiency reports (66), workers reported that zinc sulfate was highly injurious to wheat; crop yields were much greater in earthenware than in zinc pots and that the injurious effects were largely overcome by liming;

and that burying zinc plates in soil resulted in injury to plants. A very small difference exists between adequate and toxic zinc. This was illustrated in a report showing that 0.001 mg. zinc per 100 ml. solution stimulated Chlorella, whereas 0.005 mg. retarded growth.

Other workers (23) found that replaceable zinc in milliequivalents per 100 grams of soil became toxic for corn between 0.688 and 1.376 on a Norfold sand, between 0.758 and 1.137 on an Orangeburg fine sandy loam, and between 1.615 and 2.153 on a Greenville clay loam. The value for cowpeas was appreciably lower. Calcium carbonate reduced the toxicity.

In New York state (60), zinc toxicity was noted on peat soils. A laboratory analysis of these soils reported that the zinc content was 23,600 p.p.m. and that it was held in an exchangeable form. Best results in decreasing toxicity were obtained by applying calcium hydroxide.

Levels of zinc which will induce deficiency and excesses in most plants vary approximately by a factor of 20, or 2,000%. Limited information also suggests that amounts greater than 400 p.p.m. are excessive (1).

There are indications that the application of zinc, though not directly toxic, interfered with iron metabolism and induced iron chlorosis of citrus seedlings growing in vermiculite solution cultures (58).

The roles of copper and manganese in inducing iron chlorosis have received far more attention than zinc. One concept that has much support is competition of the metals for organic complexes in plants.

It is believed that the order of toxicity of metals is reasonably close to the order of stability of metal organic complexes (28):

$$Cu^{++} > Na^{++} > Co^{+++} > Fe^{+++} > Zn^{++} > Cd^{++} > Fe^{++} > Mn^{++} > Mg^{++}$$

There was only one report (Maine) indicating that large amounts (110 pounds) of zinc sulfate applied to potatoes depressed yields (25). None of the workers described the symptoms of toxicity other than noting that the growth was not normal.

ZINC CONTENT OF SOILS

Zinc is almost universally distributed in soils. The total amount seems to vary with the parent rocks and with the type of weathering processes (65). Variations of this concept have been found. Utah workers (64) found that soils formed from limestone contained more zinc than soils formed from gneiss or quartzite, even though samples of parent rock contained similar amounts.

Zinc deficiencies seem to occur principally in sandy soils formed from siliceous rocks such as gneiss, quartz, or sandstone because of their low zinc content. The major zinc containing ore deposits found in the United States are listed in Table 2 (48).

Table 2. Zinc containing ore deposits of the United States.

Common name	Chemical formula	% Zinc
Sphalerite	ZnS (zinc sulfide)	67.0
Zincite	ZnO (zinc oxide)	80.3
Smithsonite	$ZnCO_3$ (zinc carbonate)	52.1
Willemite	$ZnSiO_4$ (zinc silicate)	58.6

Zinc content of Utah soils ranged from 30 to 250 p.p.m. (64), Nova Scotia soils (19) averaged 43 p.p.m., and California soils (31) 1 - 5 p.p.m. Tables 3, 4, and 5 show the variability of zinc content and availability in Utah (64), and California (31) soils.

A thorough review (70 papers) of data containing information on the amount of total or extractable zinc in various soils indicated that 80 p.p.m. of zinc is an average value for the lithiosphere (61). Most soils contained between 10 and 300 p.p.m. of total zinc although one soil was reported with a zinc content of 16 per cent.

The greatest concentrations of zinc in the soil profile appear to be at the surface horizons and the lowest in the subsoil (1, 24, 64, 65, 79). In the Dakotas, actual measurements of zinc in the top four feet of soil resulted in finding two-thirds of the available zinc in the uppermost foot (18).

A California worker (31) reached a similar conclusion and added that this concentration was greatest in soils that had accumulated organic matter from leaf fall and other plant residues for long periods. He concluded that zinc is enriched in the surface soil by vegetative residues and that this may be a major factor in zinc deficiencies of deep-rooted plants.

Rogers et al. (53) were able to show that the growth and decomposition of native weeds and grasses in a plat increased the zinc content of the surface soil by 70 p.p.m. (average) after one year, and 140 p.p.m. (average) after two years.

This concept has been confirmed by other workers (24, 64, 79).

Table 3. Average zinc content of various groups of Utah soils. (Parts per million)

Soil depth	Noncalcareous soils				Calcareous soils	
	Zinc-deficient areas		Zinc-sufficient areas			
	Total	Available	Total	Available	Total	Available
Topsoil	146	5.9	181	6.03	301	12.4
Upper subsurface	117	2.6	101	3.40	265	10.4
Lower subsurface	81	2.6	87	4.03	238	10.5

Table 4. Zinc content of various rocks.

Type of rock	Source	$CaCO_3$ content	Total zinc	Available zinc
		per cent	p.p.m.	p.p.m.
White marl (Pliestocene-Bonneville)	White Valley, Utah	56.6	578	0.0
Limestone (Miss.-Brazer)	Big Cottonwood Canyon	42.0	673	0.0
Limestone (Miss.-Brazer)	Big Cottonwood Canyon	42.8	518	0.0
Fresh water algal limestone (Eocene-Flagstaff)	Thistle Canyon	37.9	550	0.0
Limestone (Pliocene?-Salt Lake)	Collinston area	31.0	652	0.0
Limestone (Miss.-Madison)	Providence Canyon	38.2	528	0.0
Gneiss (Archaeozoic-Farmington Canyon complex)	Kaysville area	--	725	1.0
Quartzite (Algonkian)	Cottonwood Canyon	--	345	1.2
Quartzite (Penna.-Oquirrh)	Provo Canyon	--	527	0.0
Quartzite (Cambrian-Brigham)	Bakers Canyon, Brigham	--	871	4.0
Granite (Cottonwood-Tertiary)	Alpine	--	750	8.4
Gneiss, partly weathered (Archaeozoic-Farmington Canyon complex)	Kaysville area	--	285	8.5

Table 5. Lowest and highest quantities of available zinc found in groups of soils from widely separated localities.

Group	Sample numbers	Depth	Zinc	
			Lowest	Highest
		inches	p.p.m.	p.p.m.
1. Silty clay loams from hills about Berkeley, showing variation within an area 1 mile in diameter and differences between topsoil and subsoil	1-16	1-6	1.9	4.4
		6-20	1.1	2.3
2. Similar to, and from same range of hills 3 to 4 miles south of group 1	49-54	1-6	2.2	5.8
	52	1-6	---	22.2
	117	0-2	---	94.0
3. Silty clay loams from somewhat level northwest part of the City of Berkeley near the Bay of San Francisco	40-48 (7 samples)	1-20	2.3	7.0
	38, 39, 43	1-6	12.0	13.3
4. From Moraga Ridge 3 miles east of group 2	119-120 (shaly loams)	1-6	2.2	5.1
	118-122 (high organic forest mull)	0-2	20.0	32.7
5. Leaves and silt loams from Mt. Tamalpais region of Marin County just north of the Golden Gate	55-59 (south side of mountain)	0-6	1.1	7.2
	106-109 (north side of mountain)	0-6	1.6	5.2
6. From San Bruno Hills, just south of San Francisco	32-35 (loams)	0-6	1.2	2.7
	133 (dune sand)	0-6	---	4.0
7. From east side of lower San Joaquin Valley, nearly level	78-79 (loams)	0-6	0.3	2.0
	91-94 (clay loams near river)	0-6	1.6	5.6
8. Loams and clays from Sierra Nevada foothills, El Dorado County	80-90	0-6	0.3	2.6
9. Cashion Creek area of Contra Costa County, 10 miles east of Berkeley	17-20 (loams)	0-6	1.3	7.1
	98-105 (clay loams)	0-10	2.5	5.6

FACTORS AFFECTING AVAILABLE ZINC IN SOILS

Zinc is held firmly in the soil. It cannot be leached out by rain or by irrigation water. Likewise, it cannot be carried by soil water to the roots of the plants. Roots must grow to the zinc (71).

It must also be noted that a large part of zinc added to the soil is converted to a form which is not exchangeable but can be extracted by dilute acids. The proportion of zinc in this form increases with calcium saturation, time of reaction, and with decreasing quantities of zinc (46).

More commonly, zinc is present in adequate total amount but is unavailable to the crop because of other factors.

pH

It is commonly thought that zinc availability is at a minimum in the soil pH range of about 5.5 to 7.0. Zinc is readily available at lower pH values. As the reaction rises above pH 7.0, the situation becomes more complex. Evidence from experiments suggests that the positively charged zinc ion may be converted to a negatively charged zincate complex, such as calcium zincate, which is very insoluble (54). Thorne (66) agrees that the availability of zinc is very low when the pH is above 6.0. Nevertheless, Lazaruk (40) working in a laboratory with potatoes, indicated that a soil pH of 5.5, 6.5 or 7.5 had little effect on availability of zinc, but did affect the availability of manganese and boron.

The addition of ammonium sulfate, ammonium nitrate, and potassium nitrate will also reduce soil pH, with the greatest reduction occurring when these fertilizers were incorporated along with treble super phosphate (37). If we accept the conclusion that the availability of zinc increases as pH decreases, then with the application of the nitrogen and phosphorus carriers, more zinc should become available.

A question still remains as to the pH factor that affects uptake of zinc. Some possibilities are: that the reduction of zinc uptake is an effect of pH, rather than of calcium (76); that zinc uptake is increased with increasing proportions of complimentary H^+ ions (77); zinc deficiency is related to the carbonate level (45); or that uptake is reduced through the formation of insoluble zinc hydroxides (54).

Liming, a practice which increases the pH of a soil will decrease availability of zinc to potatoes (1, 2, 54).

Phosphate

Soils high in native phosphate may cause fixation of zinc in unavailable form (1). Heavy application or prolonged use of phosphate frequently reduces zinc uptake by the crop (1, 14, 20, 35, 41). Most workers also observed that an increased supply of zinc would alleviate the deficiency condition.

In contrast to these results, applications of 400 to 2,000 pounds of soluble P_2O_5 to either beans or peach trees (66) failed to influence the uptake of either applied or native soil zinc.

The development of the deficiency nor the elimination of the deficiency was well correlated with changes in the concentration of zinc in stem or leaf tissues. High concentrations of phosphorus in tissues resulting in high phosphorus/zinc concentration ratios appear to offer a better explanation for the metabolic upset. Healthy plants tended to have phosphorus/zinc concentration ratios less than 400, whereas in deficient plants the ratio was generally greater than 400 (8). These data indicate a mutual antagonism between phosphorus and zinc in their uptake and accumulation in the plant.

Other work cited by Thorne (66) indicates that with high concentration of phosphate the zinc does not become unavailable in the soil, but is taken up by the plant and precipitated along the veins. Under low phosphate condition, the zinc was distributed uniformly through leaves and was not markedly concentrated along the veins.

Ellis et al. (20) investigated a report that the yield of field beans, which followed sugar beets in a rotation was reduced by approximately 50%. The results of the investigation were that zinc deficiency was due to a high application (175 or 350 pounds) of phosphate. Their data supports the conclusion that zinc-phosphorus interaction is either at the root surface or within the plant.

Organic Matter

Zinc deficiencies have been observed in old barnyard or corral sites (1) and zinc toxicity reported from peat soils in New York (60). Workers (24, 64, 79) have shown that surface soils are higher in zinc content than subsoils because of leaf fall and other plant or animal residues and that a growing plant will utilize zinc from the soil and deposit it on the surface as the plant decomposes.

In another instance, manure was added to an exposed subsoil alleviating zinc deficiency (24) and yet another observation that frequent uses or large amounts of poultry manure may induce zinc deficiency (1).

There is some evidence that zinc may be absorbed or complexed by organic matter (66) while Hibbard (31) failed to obtain significant releases of zinc in several soils by oxidation of organic matter with hydrogen peroxide.

Land Leveling

The results of an experiment in North Dakota indicated that two-thirds of the available zinc in the top four feet of soil was found in the uppermost foot (18). If this is a fact, then it is conceivable that land leveling for irrigation, a practice which will expose the subsoil and bury the top soil, will decrease the amount of zinc for the following crop. Grunes et al. (24) have also observed the tendency for leveled land to be deficient in zinc.

Others

Crop Rotation: Zinc deficiency has been found more frequently after a crop of high zinc uptake such as sugar beets, than after sorghums or potatoes which have a low uptake of zinc (9).

Clay: Clay soils of high magnesium content may also fix zinc in unavailable forms by strong adsorption on the clay minerals in place of magnesium (1). The studies of zinc solubility in soils are in agreement with the general tendency of this element to form many compounds of low solubility. Precipitation of zinc as the hydroxide, carbonate, or phosphate can reduce soluble zinc in soils to low levels (66).

Temperature: Observations noted that zinc deficiencies on corn often disappeared in July. Bauer and Lindsay (3) conducted an investigation to see if temperature was the factor affecting zinc availability.

Corn was grown uniformly on a perlite media, irrigated with minus zinc half-strength Hoagland solution and was later placed in contact with a zinc deficient soil which was subjected to a temperature of 109.4° F. for a period of 0, 1, 3, and 6 weeks. The results are summarized in Table 6.

Table 6. Zinc uptake by corn.

Period of soil incubation	Dry matter yield of corn tops	Total zinc uptake by corn
weeks	gm/pot	μgm/pot
0	4.40a	38.8k
1	7.76c	81.4m
3	6.91d	71.6ml
6	5.88b	60.6l

Numbers followed by the same letter are not significantly different at the 5% confidence level.

The results indicate that incubation at 109.4° F. was instrumental in releasing available zinc and this resulted in increased plant growth. The greatest release of soil zinc was realized after one week incubation but declined with prolonged period of incubation. A tentative conclusion was offered that prolonged incubation caused a refixation of the zinc released during the initial incubation. That zinc was a limiting factor of growth was demonstrated by deficiency symptoms of the plants, low zinc concentration in the tissues, and growth response when zinc fertilizer was added to the soils prior to soil-root contact.

The work was summarized as strongly suggesting that temperature relationships can greatly modify the available zinc status of soils possibly through the effects of temperature on microbiological activity.

Work in Michigan (20) indicated that a decrease in soil temperature from 75° to 55° F. decreased zinc uptake in corn.

Nitrogen: The source of nitrogen seems to affect the uptake of zinc into the top of the potato plant (9). The carriers used and the amount of concentration and uptake in p.p.m. are as follows: Ammonium sulfate, 22.4, .039; Ammonium nitrate, 18.0, .031; and Calcium nitrate, 15.6, .027. When no nitrogen was used the zinc uptake was .012. Sixteen pounds of zinc applied per acre without nitrogen produced higher zinc concentration. Total zinc uptake from these plots to which 16 pounds of zinc had been applied, increased generally as nitrogen application increased the size of the plant.

Iron: Work being done with iron elements has indicated that adding zinc to some soils interferes with the iron metabolism in plants (41, 58), and also that additional iron on zinc deficient soils increases the zinc deficiency problem (41).

SOIL TESTS FOR ZINC

The traditional research technique for testing the zinc status of soils and plant tissue is to analyze samples by chemical and biological means. Considerable effort has gone toward devising soil tests that will differentiate soils containing inadequate available zinc for normal plant growth. Only those which have shown value, and merit further study, will be discussed.

Chemical Tests

Hibbard (29) developed the dithizone method for quickly measuring small amounts (five to ten per cent) of zinc commonly present in animal, vegetable, and many other substances. Using this method, the zinc must first be brought into solution by suitable means. The solution is made alkaline by ammonia, a chloroform solution of dithizone is added, and the mixture is shaken and let stand a minute to separate. If zinc is present it combines with the dithizone in chloroform and colors it red. The intensity of color is proportional to the amount of zinc, which will be in the range of 0.001 to 0.100 mg. This method is not adapted to measurement of amounts much greater than 0.1 mg.

In 1940, Hibbard (30) developed an extracting reagent consisting of a 0.5 m KCL solution adjusted to pH 3.2 with acetic acid. A 5-gram sample of soil was extracted with 400 ml. of the solution, and zinc in the extract was determined by the dithizone method. This method was used to test 140 samples of soil and rocks collected in California and the extracted zinc ranged from 1 to 5 p.p.m. In a later modification of the method, Hibbard (30) found that extending the extracting period from a few hours to several days improved the relation between extracted zinc and uptake by plants.

Wear and Sommer (77) compared the Hibbard methods and concluded that the shorter method gave as satisfactory a relation to zinc deficiency symptoms as did the longer method on acid soils.

Other workers (64) working with Utah soils found no consistent correlation between any of the factors: total zinc, zinc extracted by Hibbard's method, organic matter content, or pH. They concluded that total zinc differentiated zinc deficient soils as well as the extraction procedures of Hibbard.

Holmes (32) modified the dithizone method by determining zinc by the A. O. A. C. dithizone method. This procedure was found to be satisfactory for all but highly calcareous soil samples (45).

Shaw and Dean (55) extracted soil samples with a two-phase system of aqueous ammonium acetate and carbon tetrachloride containing dithizone. They obtained a good relationship between extracted zinc and the incidence of zinc deficiencies in crops.

Massey (43) reported a definite relation between soil factors and the plant uptake of zinc. The soil pH was negatively correlated, and the dithizone-extractable zinc was positively correlated with uptake of zinc.

Viro (74, 75) used a solution of ethylenediaminetetracetic acid (a chelating agent for heavy metals) to extract acid forest soils. A good correlation between zinc removed in the extract and the fertility status of the soil was obtained. Zinc content of the soils was reported to range from 2.41 to 9.95 p.p.m. or 2.23 to 18.6 pounds of zinc.

Nelson et al. (45) devised a method for calcareous or high pH soils. The method consists of plotting acid-extractable zinc against the "titratable alkalinity" of a soil, which is defined as the milleequivalent of acid required to titrate the soil to pH 5.0. A good separation of zinc deficient and zinc non-deficient soils was obtained with soils from seven western states.

Aspergillus niger test

Many early zinc investigators, cited by Thorne (66), found that the common soil fungus, Aspergillus niger, requires a good supply of available zinc for optimum growth (Raulin, 1869; Bertrand and Javillier, 1911; Javillier, 1912; Gollmick, 1936). Recently, the A. niger test has been used extensively for estimating the zinc-supplying power of soils (Gerretsen, 1948; Nicholas and Fielding, 1951; Donald et al., 1952; Bould et al., 1953).

In the A. niger method used by Nicholas (47), zinc is extracted from the soil or sample with an extract of dithizone in carbon tetrachloride at pH 4 or coprecipitation with Fe using 8 hydroxyquinoline at pH 6. The zinc extracted is added to a culture solution that contains all of the other nutrients and the solution is inoculated with the fungus (Aspergillus niger, Mulder's M strain) and incubated. The growth of the fungus is proportional to the amount of 'test' nutrient (zinc) it derives from the material added, and the growth reflects the range from deficiency to sufficiency levels.

Nicholas obtained a correlation on zinc deficiency in soils where apple and pear trees showed "little leaf", a zinc deficiency symptom.

Tucker et al. (70), estimated zinc status of Illinois (acid) soils with the A. niger method and found that Illinois soils ranged from 1.6 to 21.5 p.p.m. zinc. Florida soils known to respond to zinc fertilization ranged from 0.6 to 2.88 p.p.m. zinc. Therefore, they concluded that a few Illinois soils may respond to zinc fertilization or are at least approaching the critical level.

Tucker and Kurtz (69) conducted a study of soil zinc utilized by the Aspergillus niger bio-assay test in comparison to zinc extracted by 0.1 N HCL, acetic acid, EDTA and the dithizone methods. The amounts of zinc extracted were significantly correlated with the bio-assay values. They concluded that the dithizone procedure of Shaw and Dean is more rapid and simple although the technique requires some skill. The Versenate (EDTA) extraction is less adapted to routine use since destruction of the versenate, an extra step, is necessary before zinc is determined. The 0.1 N HCL extraction is also simple and rapid and would probably be preferred procedure for humid non-calcareous soils and where both acid and calcareous soils are encountered, the Shaw and Dean dithizone procedure would be preferable for routine analysis. The bio-assay procedure, which removed more zinc than any of the extracting solutions, requires about eight days for incubation and completion of analysis. Actual working time per sample, however, is less with the bio assay than with any of the chemical methods.

CONTROL OF ZINC DEFICIENCY

Four general procedures for the control of zinc deficiency in potatoes will be discussed. First, management practices; second, soil treatment with zinc-containing minerals; third, application of zinc-containing sprays or dusts; and fourth, seed treatment. The following recommendations are based on research conducted under specific conditions. Results, therefore, might be different when applied under other conditions.

Management

<u>Crop rotation including alfalfa</u>: Growing alfalfa has helped increase the availability of zinc to the crops that follow (66). The

beneficial effects are the result of the deep, feeding roots bringing the zinc to the surface, and there is also evidence that alfalfa increases the available zinc supply to plants growing in association with it. Do not follow a crop that is a heavy user of zinc (sugar beets) with a zinc sensitive crop as potatoes.

Green or organic manures: Green manure crops, weeds or grasses will take up zinc and release it through decomposition (53). Weeds and grasses from plats rested one year averaged 70 p.p.m. of zinc and those rested two years averaged 140 p.p.m. Add organic manures to supply necessary zinc (24).

Erosion: Since the surface layer contains most of the available zinc, guard against abnormal soil erosion (71).

Phosphates: Apply at recommended rates. Higher rates can cause zinc deficiency to appear (71).

Soil Treatments

Significant yield responses were recorded when zinc sulfate was broadcast or sidedressed and disced into the soil (7, 14, 24, 36, 63, 71). Other zinc carriers can be used with equal success and are listed on Table 7. So far the merits of chelated zinc for crops has not offset the higher cost (71).

Just recently, work comparing seed treatment, foliar application, and soil treatment of zinc sulfate concluded that the best response was from the soil application (35). For a soil treatment, the zinc sulfate should be broadcast and thoroughly disced or plowed into the soil, and zinc thus applied is available to plants for four to five years, perhaps longer (71).

Table 7. Inorganic sources of zinc.

Common name	Chemical formula	% of zinc	
Zinc sulfate monohydrate	$ZnSO_4 \cdot H_2O$	35	(48)
Zinc sulfate heptahydrate	$ZnSO_4 \cdot 7H_2O$	23	(48)
Basic zinc sulfate	$ZnSO_4 \cdot 4Zn(OH)_2$	55	(48)
Zinc oxide	ZnO	80	(71)
Zinc carbonate	$ZnCO_3$	38	(71)
Ethylenediaminetetraacetate		14.2	

A general recommendation for potatoes calls for broadcasting 20 - 40 pounds of zinc sulfate or 7 - 14 pounds of zinc or banding with 10 pounds of zinc sulfate (4 pound zinc) per acre and work deeply into the root zone (1, 14, 24).

Fertilizer manufacturers could add zinc sulfate to mixed fertilizers so that only one operation would be necessary (54).

A survey of commercial fertilizers for their zinc content indicated that most fertilizers contain zinc in varying amounts depending on the source of raw material. Some of the more common fertilizers manufactured in the United States and their zinc content are shown in Table 8 (62).

Spray application

Spray applications of zinc on potatoes have produced significant increases in yield. Fungicides (Dithane Z-78 and Zerlate), Chelates (EDTA) and inorganic zinc salts were used with significant yield responses (24, 27, 34).

Table 8. Zinc content of commercial fertilizers in U.S.

Fertilizer	Zinc content p.p.m.
Ammonium nitrate	4 - 5.6
Ammonium sulfate	Trace to 800
Ammonium sulfate (USA mean)	295
Phosphoric acid (Idaho)	300
Phosphoric acid (Florida)	150 - 4800
Superphosphate (Florida)	50 - 165
Superphosphate (Idaho)	417 - 478
Treble superphosphate (USA mean)	700
Potassium sulfate (USA mean)	8.0

There are indications that spray applications are not as effective as soil applications (7, 24, 36, 71).

In correcting zinc deficiencies on varieties other than Russet Burbank, use 0.4 to 1.4 pounds of metallic zinc to 100 gallons of water with a spreader-sticker and apply under low pressure. Wet the foliage thoroughly. One or more repeat applications may be necessary (34, 71). Best results are obtained when the application is made early in the growth period or at least when the plant is still in a vigorous growth period (71).

For a spray test for zinc deficiency, mix one teaspoonful of zinc sulfate in a gallon of water and wet the foliage of several suspicious plants. If zinc is deficient, the plants should resume normal growth. New leaves and stems should show no signs of deficiency. Response is usually obvious in ten to fourteen days (71).

A tentative classification of field and vegetable crops as to their vegetative response to zinc (foliar or soil application) was established and is shown on Table 9 (72).

Table 9. Classification of crops to vegetative response to zinc.

Very sensitive	Mildly sensitive	Insensitive
Beans	Alfalfa	Asparagus
Castorbeans	Grain sorghum	Barley
Corn	Onion	Carrots
Flax	Potatoes	Grasses
Grapes	Red clover	Mustard
Hops	Sudan grass	Oats
Lima beans	Sugar beets	Peas
Soybeans	Tomatoes	Peppermint
		Rye
		Safflower
		Wheat

Tuber Treatment

Response from this treatment has been erratic. Nova Scotia (19), Prince Edward Island, Manitoba, and British Columbia (16), potato growers have used this practice with significant increases in yield. Most workers in the United States did not measure a significant response from this method. Workers did note that the zinc treated seed pieces had more rapid emergence but probably due to control of seed piece decay (16).

Seed pieces are soaked in a 0.08 N solution of zinc acetate or sulfate for two minutes and then planted. Other seed treatment solutions consisted of five pounds of zinc sulfate to 100 gallons of water (16).

SUMMARY

The knowledge that zinc is essential to plant growth has been known for quite some time, yet the role the minor element plays in plant growth is not fully understood. The plant requirements for zinc are low but despite the small amounts required in relation to the major elements, they are equally essential for normal plant metabolism.

Zinc deficiencies have been recorded in the major potato producing areas of the United States. It does not seem to be a general problem but is localized within a given area or field. These deficiencies are apt to be found where the parent material of soil is low in zinc content, in eroded areas, where land has been levelled, or where it has been removed by successive cropping. Occasionally total zinc content is high but unavailable due to other soil factors such as high pH, low temperatures, or high organic content. A few cases have been reported where the zinc content of the soil was sufficiently high to cause toxicity to plants.

Symptoms of zinc deficiency have been recorded on the Russet Burbank and Red Pontiac potatoes. These deficiency symptoms appear to be different for each variety but there is a possibility that this difference is due to different environmental conditions.

The function of zinc in the plant is not clearly understood. There is sufficient evidence that zinc plays a direct role in the synthesis of tryptophan and indirectly for the synthesis of auxins. There is some indication that zinc is a component of several enzymes which regulate the various metabolic activities within the plant.

Chemical and bio-assay tests have been devised to determine the zinc content of different soils, and a correlation of test results and deficiency symptoms have been obtained. Significant yield responses from soil and foliage applications of zinc bearing materials have been recorded for various areas. It seems that the most efficient method of control is by broadcasting and discing zinc into the soil. As zinc does not readily leach or move in the soil, this distribution allows for maximum root contact by the potato plant. Foliage applications can be made, and to get the best response, material should be applied when the potato plant is still in a vigorous growing condition.

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