AGRONOMIC APPROACHES TO INCREASING ZINC CONCENTRATION IN STAPLE FOOD CROPS

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Summary

The literature on agronomic measures that can result in increased concentration of Zn in the grain of major crops was reviewed. Concentration of Zn in the grain varies over a relatively large range, but there appears to be a functional barrier to excessive accumulation of Zn in the grain, regardless of the Zn supply. Inorganic Zn fertilizers are a relatively cheap source of Zn for soil and foliar applications; their effects in increasing the grain yield and Zn concentration compare favorably with those of more expensive chelated fertilizers. While foliar fertilization is an effective way of increasing Zn concentration in the grain (because Zn is relatively easily transported in the phloem),

soil fertilization with Zn is necessary in Zn-deficient soils because the lack of sufficient Zn early in the crop development may predispose plants to grain yield losses that later fertilization will not alleviate. Zinc in organic matter is generally slowly available to plants, but mixing inorganic Zn fertilizers with manure or other organic matter may be an effective source of Zn for crops. Supplying Zn through seed soaking and seed coating may result in increased crop yields in Zn-deficient soils, but not in an increase in grain Zn concentration. There are commercially available genotypes of major staple crops that are more Zn-efficient than the standard cultivars; Zn-efficient genotypes not only grow better on soils with low Zn availability, but may sometimes produce grain with higher Zn concentration. The potential of mycorrhizae to contribute to Zn nutrition under field conditions remains to be properly evaluated. As a result of increased supply of Zn, Zn concentration in various parts of the grain increases to a different extent, necessitating changes in the milling practices to retain in the human diet the benefits of field fortification of the staple grain with Zn.

1. Introduction

Micronutrient-deficient soils are widespread; many millions of hectares of arable land worldwide are deficient in one or more micronutrient elements. Soils with low plant-available Zn (=Zn-deficient soils) are common in tropical and temperate climates, but are most widespread in regions with the Mediterranean type of climate, including the cropping areas of Western and South Australia. Zinc deficiency was reported for soils of various characteristics: high and low pH, high and low organic matter, calcareous, sodic, sandy, wetland or ill-drained, limed acid soils, etc. In rice, Zn deficiency is common on neutral to alkaline pH soils containing more than 1% organic matter as well as on calcareous soils used for upland rice production.

Crops grown on Zn-deficient soils frequently produce grain that has low Zn concentration. When such grain is re-sown in the following year, the new crop arising from the seed is likely to have low germination rates, reduced seedling vigor, greater susceptibility to soil-borne root and crown diseases, slow canopy development, poor competitiveness with weeds and a lower yield potential. Such grain with low nutrient concentration would also provide inadequate Zn nourishment when used in human diet.

Most crop management practices are aimed at achieving yields close to the maximum potential yield possible in a given environment. As predicted by the law of diminishing returns, increased additions of micronutrient fertilizers to deficient soils result in a saturable yield response of a crop. It is generally accepted that the best economic returns are obtained at about 90 to 95% of the maximum yield. In contrast, concentration of Zn in cereal grain increases with an increase in Zn fertilizer additions, showing much less saturation in the response. An implication is that amounts of Zn fertilizers in an excess of what is required for achieving 90% (or even 100%) of the maximum yield may result in increased concentration of Zn in grain.

Nutrient concentration in plant tissues is frequently inversely related to dry matter accumulation in that tissue, causing an ill-described phenomenon of ‘dilution’. This dilution occurs mostly in tissues that have a fast growth rate; dilution occurs when a growth rate is faster than the corresponding uptake rate of nutrients from environment or the rate of transport of nutrients into a particular tissue (e.g., loading into seed). It should be borne in mind that the Zn density (=concentration, representing the amount of Zn per unit of grain dry weight) is a more important measure of Zn supply in the grain destined for human food than Zn content (the total amount of Zn per seed or plant).

Comprehensive agronomic approaches, including specific fertilization strategies, aimed at enhancing seed micronutrient concentration have yet to be designed. However, fertilization aimed at increasing grain micronutrient density to allow good crop establishment when seed is re-planted in nutrient-deficient soil has been reported occasionally. This paper will summarize the limited information that currently exists on Zn concentration in grain of common staple crops as well as in some root crops (cassava and yam). The influence of various agronomic measures (amounts, timing, placement and form of fertilizers, organic matter, crop and variety selection, crop rotations, etc.) on increasing Zn concentration in staple food crops will be described. While the focus will be on Zn, other nutrients will also be mentioned.

2. Variation in Zn Concentration in the Grain

Concentration of nutrients in seed is dependent on soil type, nutrient availability, crop species, and to a lesser extent, season and variety. Table 1 summarizes variation reported for Zn concentration in the grain of various crops. These ranges should be a useful guide for assessing variations caused by environmental factors and other factors discussed in the present paper. It is important to note that bread wheat (*Triticum aestivum* L.) showed a wider range of grain Zn concentrations compared to other crops (Table 1). However, the high concentration of Zn in the wheat grain was achieved in the glasshouse pot trial where sufficient amounts of Zn were added to cause Zn toxicity and therefore a grain yield decline.

Species	Zinc concentration in grain
	(mg kg^{-1})
Wheat *(Triticum aestivum)*	5-162
Triticale (*X Triticosecale* Wittm.)	10-37
Rice *(Oryza sativa)*	6-95
Maize (*Zea mays*)	12-45
Barley (*Hordeum vulgare*)	6-31
Pearl millet (*Pennisetum glaucum*)	13-51
Sorghum *(Sorghum bicolor)*	23-43
Soybean *(Glycine max)*	24-61
Bean *(Phaseolus vulgaris)*	13-38
Chickpea (C*icer arietinum*)	38-50
Cowpea (*Vigna unguiculata*)	16-54
Canola *(Brassica napus)*	7-40

Table 1. The range of grain zinc concentrations in various crops. The results from the glasshouse experiments where plants had been grown to maturity were included together with the results on field-grown crops. The data are from experiments where widely different growing conditions and a large number of genotypes were tested; therefore, the data on different species are not directly comparable. Compiled from a variety of sources. Compare with Zn concentration of 16-52 mg Zn kg^{-1} dry weight in yam (*Dioscorea ssp*.) tubers.

The reported data indicate that plants tend to maintain Zn concentrations in the grain within certain limits, but changes in the growing conditions (including application of fertilizers) can alter the balance. Understanding the factors that influence such a balance may be important when trying to increase Zn concentration in the grain.

There appears to be only a weak relationship between the grain concentration of Zn and the concentration of other micronutrients. This is in part attributable to the non-synchrony of the deposition of different micronutrients into the developing grain. However, the comparison of concentrations of nutrients in barley grain of a number of genotypes grown in seasons 1983/84 and 1989/90 in southern Australia (seasons were similar and produced high-yielding crops) revealed that concentration of K was higher but concentrations of P, S, Mg, Ca, Zn and Mn were all lower in the 1989/90 than in the 1983/84 seasons. The study indicated that changes in Zn concentration in the grain could occur simultaneously with changes in the concentration of other nutrients within a relatively short time-span.

While the total content and concentration of Zn vary in grain of different species due to differential Zn supply, soil characteristics, seasonal and genotypic variation and other factors, much greater difference in Zn concentration in the grain exists between crops species and some wild species adapted to Zn-deficient conditions (see *Improving the Nutritional Quality of Maize and Wheat for Human Consumption* and *Improving Micronutrient Value of Rice Through Breeding* and *Improvement of Common Bean for Mineral Nutritive Content at CIAT*). These species may have Zn concentrations in seed an order of magnitude greater than cultivated species. In addition, wild species can remobilize a much larger portion of Zn from their vegetative tissues and load it into the grain, hence depleting Zn in vegetative tissues to the concentrations as low as 2 to 3 mg Zn kg^{-1} dry weight. The physiological mechanisms behind such a difference between wild and crop plants in the capacity to remobilize Zn from vegetative tissues and load it into grain are unclear; further research is not only warranted but should be treated with urgency, given the great interest in increasing the capacity of staple grain crops to load Zn into grains destined for human food.

It should be pointed out that increased Zn concentration in wheat grain and therefore in flour will not have adverse effects on the bread making quality of flour. Quite the contrary, recent research has showed improved loaf volume and crumb grain, enhanced film-coating properties of gluten and no ‘off-taste’ of Zn-enriched bread when compared with control bread.

3. Variation in Zn Concentration in Root Crops

Cassava (*Manihot esculenta* Crantz) contains high concentrations of all nutrients, including Zn, in leaves, while K is present in high concentrations in roots and Zn in tubers. In general, fermentation of cassava could improve the bioavailability of mineral nutrients, but did not influence Zn in grated cassava. However, Zn content was decreased when cassava was soaked in water (for the preparation of fufu and lafun, the local food in many parts of Africa).

Zinc concentrations in tubers of four common species of yams (*Dioscorea piscatorium*, *D. wallichiani*, *D. hispida* and *D. alata*) were 16-52 mg kg^{-1} dry weight, the highest concentration of all trace elements. Zinc concentration in tubers of 20 different genotypes belonging to seven species of edible yams did not vary significantly before and after boiling and in flour. In addition, Zn concentration was not different between the bark and the fleshy tuber tissues of the two genotypes of *D. rotundata* (white yam). These results suggest little loss of Zn in preparation of yam for food.

4. Effects of Macronutrient Fertilizers in Increasing Zn Concentration in Staple Food Crops

The widespread use of macroelement fertilizers to raise crop yields makes them a convenient vehicle to supply crops with micronutrients as well. Indeed, micronutrients are commonly added to macronutrient fertilizers during the manufacturing process (e.g., in Australia, Zn, Cu and Mo are usually added to the superphoshate; in India, zincated urea as well as Zn-superphosphate are used). Alternatively, micronutrients present as impurities in fertilizers may make a significant contribution to micronutrient supply to crops.

Increased concentrations of macronutrients (e.g., P and N) in grain may sometimes be associated with higher grain concentration of Zn. For example, an average increase in grain Zn concentration of 4 mg kg^{-1} was measured when wheat was fertilized with 160 compared to 40 kg N ha^{-1}. In contrast, an application of P to wheat, narrow-leafed lupin (*Lupinus angustifolius* L.) and triticale (*×Triticosecale* Wittm.) grown on a P-deficient site did not result in a change in Zn concentration in grain. Nitrogen fertilization of wheat in the field trial also did not result in a significant increase in grain Zn concentration. In *Triticosecale* breeding lines, fertilized with different levels of NPK for increasing yields and having a relatively wide range of Zn concentrations in the grain (20 to 37 mg kg^{-1}), a clear negative relationship between yield and grain concentration of nutrients was noted.

Foliar symptoms of Zn deficiency could appear on field-grown cassava fertilized only with macronutrients, especially after prolonged cropping of soil without Zn fertilizer inputs. Such an effect is due to diminishing of available pools of soil Zn by high production of crop dry matter.

5. Effects of Zn Fertilizers in Increasing Zn Concentration in Staple Food Crops

Zinc-deficient soils may have low total Zn content (e.g., some leached acidic soils in tropics) or may have a relatively large total Zn content, but the plant-available fraction is low because of soil chemistry favoring formation of sparingly soluble Zn complexes. Zinc fertilizers would generally be expected to be more effective in soils with low total Zn content to begin with. Zinc fertilizers can also be effective in soils low in plant-available Zn, but combinations with other strategies (e.g., foliar fertilization, Zn-efficient genotypes, mycorrhiza, etc.) should be pursued together with Zn fertilization in such a case.

Zinc deficiency affecting crop yields is difficult to eliminate because: (1) there is a large temporal and spatial variation in availability of soil Zn, (2) a relatively large portion of soil-applied Zn may be fixed into plant-unavailable forms, and (3) soil-applied Zn is not readily transported down the soil profile. Therefore, the effectiveness of application of Zn to the soil in increasing the grain yield and, even more so, grain Zn concentration can be significant only in a well-defined set of circumstances. Extrapolating the results to a new situation is unlikely to be successful without a specific adjustment in the fertilizer practice.

While foliar fertilization can be timed to coincide with the period of intensive loading of Zn into the grain, soil-applied fertilization generally cannot. The knowledge about Zn uptake from the soil-applied fertilizers, transport of Zn within the plant and Zn loading into the seed therefore become more critical. The amount of Zn loaded into the grain represents the sum of Zn being transported directly from the soil solution, or from foliar fertilizers, plus Zn that is remobilized from vegetative tissues. However, little is known about the mechanisms governing remobilization of Zn from vegetative tissues into the grain (see Section 7).

Soil and foliar applications of Zn and the use of various soil amendments (organic matter, sewage sludge, lime) is reviewed below, together with other approaches (use of Zn-efficient genotypes, the role of mycorrhiza in Zn uptake and transport) that are aimed at increasing Zn concentration in grain and root crops. Other ways of delivering Zn fertilizers (dipping seed in Zn-containing solutions, seed dressing and seed coating) will be mentioned briefly.

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Biographical Sketch

Professor Zed Rengel, B.Sc. Hons, M.Sc. (Zagreb Univ., Croatia), Ph.D. (Louisiana State Univ., USA), currently Head of Soil Science and Plant Nutrition, University of Western Australia, has over 18 years of experience in aluminium and heavy metal toxicity, plant nutrition, soil fertility, biology and chemistry of rhizosphere, and modelling of soil-plant interactions. He teaches soil fertility, plant nutrition and ion toxicity to students in agriculture, natural resource management and science. He is the author/co-author of 130 publications in refereed journals and 15 book chapters. He has edited two books and is finishing two more. He has won 48 competitive research grants. He has been awarded four prizes and 14 Fellowships (including Humboldt, IEAE, OECD, Commonwealth, Japanese STA, etc.) and Visiting Professorships (Cornell, Okayama). He has given 12 keynote addresses, has chaired 11 scientific sessions at international Conferences, and has presented seminars at 25 Universities and Professional Societies in 12 countries. He is an Editor of three journals (*Plant and Soil*, *Journal of Plant Nutrition*, *Journal of Crop Production*), is on the Advisory Editorial Board of two journals and is a referee for an additional 14. He is a consultant to various industries, Universities and also to the Government. He has supervised 18 postdoctoral fellows, 24 postgraduate and 22 Honours students.