MICRONUTRIENTS IN SOILS, CROPS, AND LIVESTOCK

土壤、农作物中及家畜体内的微量营养元素

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Abstract: Micronutrient concentrations are generally higher in the surface soil and decrease with soil depth. In spite of the high concentration of most micronutrients in soils, only a small fraction is available to plants. Micronutrients, also known as trace elements, are required in microquantities but their lack can cause serious crop production and animal health problems. Crops vary considerably in their response to various micronutrients. *Brassicas* and legumes are highly responsive to molybdenum (Mo) and boron (B), whereas corn and other cereals are more responsive to zinc (Zn) and copper (Cu). Micronutrient deficiencies are more common in humid temperate regions, as well as in humid tropical regions, because of intense leaching associated with high precipitation. Soil pH is one of the most important factors affecting the availability of micronutrients to plants. With increasing pH, the availability of these nutrients is reduced with the exception of Mo whose availability increases as soil pH increases. In most plant species, leaves contain higher amounts of nutrients than other plant parts. Therefore, whenever possible, leaves should be sampled to characterize the micronutrient status of crops. Deficiency symptoms for most micronutrients appear on the younger leaves at the top of the plant, whereas toxicity symptoms generally appear on the older leaves of plants. As summarized by Deckers and Steinnes, micronutrient deficiencies are widespread in developing countries, which have much poorer soil resources than the fertile soils of Europe and North America. Many of these areas lie in the humid tropics with extremely infertile, highly weathered, and/or highly leached soils, which are intensely deficient in nutrients. The rest of such soils are in the semiarid and areas adjacent to the latter, where alkaline and calcareous soil conditions severely limit the availability of micronutrients to plants. Frequently, the Cu, iron (Fe), manganese (Mn), Zn, and selenium (Se) levels in forages, which are sufficient for optimum crop yields, are not adequate to meet the needs of livestock. Selenium is a trace mineral, which is not required by plants, and maximum forage yields can be obtained on soils with very low amounts of soil Se. However, if animals are fed feed crops and forages with low Se, they could suffer from serious muscular disorders and other diseases. White muscle disease caused by Se deficiency is the most common disorder and is found in calves and lambs. Sufficiency levels of micronutrients for crops have been discussed in relation to the animal requirement.

Key words: micronutrients; influence of micronutrient; soil; crop; livestock

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摘　要:微量营养元素通常富集在表层土壤中,其含量随土层深度递减。尽管土壤中大多数微量元素的含量很高,但只有一小部分能被植物吸收。微量营养元素,也被称为痕迹元素,所需数量微小,但其缺乏会对农作物生产和动物健康造成严重影响。农作物对不同微量营养元素有着不同的反应。芸苔和豆类对 Mo 和 B 有较高的响应度,而玉米和其他谷类对 Zn 和 Cu 较为敏感。在温润和湿热地区,由于强降雨和强淋溶作用,微量营养元素缺乏较为普遍。土壤 pH 值是影响微量营养元素对植物有效性的重要因素之一。除 Mo 以外,微量营养元素的有效性随 pH 的增加而减小,Mo 的有效性随 pH 的增加而增加。对于大多数植物来说,叶片中的微量营养元素含量高于植物的其他部分。因此,可以用叶片作为样品来测定农作物中微量营养元素的含量。大多数微量营养元素缺乏表现在植物顶部的新叶上,而过量则表现在老叶上。根据 Deckers 和 Steinnes 的结论,土壤较为贫瘠的发展中国家与土壤肥沃的欧洲及北美地区相比,微量营养元素缺乏现象较为普遍。许多营养元素缺乏区位于潮湿的热带地区,土壤极度贫瘠、高度风化和/或强淋溶,营养元素十分匮乏。此类其他土壤分部于半干旱及毗邻地区,这些地区的碱性和石灰性土壤条件严重限制了微量营养素对植物的供给。通常,可以满足草料作物生长的 Cu、Fe、Mn、Zn 、Se 含量水平,却不能满足家畜的需要。Se 是植物生长所不需要的微量元素,因此草料作物中 Se 的含量很少。然而,如果动物所食农作物和草料中 Se 含量偏低,会造成严重的肌肉异常和其他疾病。白肌病是最常见的由于 Se 缺乏造成的疾病,在牛犊和羔羊中都有发现。本文讨论了与动物需求相关的农作物微量营养元素充足度。

关键词:微量营养元素;微量营养元素影响;土壤;农作物;家畜

1 Introduction

Micronutrients, also known as trace elements or trace minerals, include those nutrients that are required in extremely small quantities by crops, livestock, and humans. This, however, in no way refers to their minor role. Their lack, e. g., in crops and livestock can cause serious crop production or animal health problems[1-3]. The chief function of micronutrients, excepting B and chlorine (Cl), is to serve as constituents of prosthetic groups in metalloproteins and as activators of enzyme reactions. Without micronutrients as a "spark plug", the enzyme system in plants would simply be an inert mass of proteins.

Increasing world population has created a serious need to increase food production. High crop yields associated with greater nutrient removal and use of high analysis fertilizers have resulted in the depletion of micronutrient reserves in soils. Deficiencies of more and more micronutrients are being observed. Crop yield and quality responses to a number of micronutrients have been reported[4-7]. Certain crops are specific in their requirement, e. g., legumes and plants belonging to the Brassicae family are particularly responsive to the trace minerals B and Mo[4,8]. On the other hand, cereals show greater responses to Zn and Cu, and sugarbeets to Mn[9-11].

The total quantity of a micronutrient in most soils is generally not a good indicator of its availability to plants[12]. However, Mo availability can be predicted to a certain extent from the total quantity of Mo in soil, e. g., on some Indian soils[13]. Soil acidity is one of the primary factors affecting the availability of micronutrients to crops[14]. With the exception of Mo and Se, the plant availability of other micronutrients decreases with liming[15,16].

Symptoms in plants caused by lack or excess of these elements and associated tissue levels are a useful guide in establishing the deficiency or toxicity of an element. It is therefore of utmost importance that we know the distribution of micronutrients in plant parts. Sampling plant parts with the highest concentration of a nutrient would assist in delineating the status of a nutrient. Since forages and to a certain extent cereals constitute a major feedstuff of livestock, it is necessary to know the effect of deficiencies of micronutrients on animal health. Some essential micronutrients and heavy metals in excess can result in toxicity to crops and or livestock[17,18].

In studies on the nutrient requirements of feed crops and forages, more attention is focused on dry matter yield response and less on animal health. The nutrient requirements for plants and livestock can differ considerably. Although extensive reviews are available on various aspects of micronutrients, this review presents up-to-date information on micronutrients and their relevance to crops and animals. The objective of this review is to report advances in research on crops sensitive to micronutrient deficiency, the relationship between the available and total micronutrient content in soil, crop responses to micronutrients, and to evaluate plant nutrient contents in feed crops as they relate to sufficiency in animals and livestock. Up-to-date information will also be presented on deficiency symptoms of micronutrients in crops and livestock.

2 Total and available micronutrients in soil

Studies on the determination of total micronutrients in soils are limited. In most soils, the total micronutrient content is not related to that potentially available to the plant[19]. However, it does indicate the relative abundance of a particular element in a soil and the potential replenishing power of a particular element[20]. However, the total content does indicate the relative abundance and can be helpful in determining its potential to some extent for Mo and B.

Studies conducted by Chatterjee et al.[21] on major soils in the north Indian plains showed that available Mn and Fe were not related to their total contents. Similar relationships were reported by Kanwar and Randhawa[22] on most soils of India. As would be expected, the total soil Fe contents were high at 5.6 to 45.6 mg • g^{-1}, and total soil Mn ranged from 107 to 1,600 mg • kg^{-1}[21]. Compared with Fe and Mn, total soil Cu contents were low and ranged from 8 to 50 mg • kg^{-1}. Zinc content in northern Indian soils ranged from 13 to 384 mg • kg^{-1} but showed no relationship with the available fraction in the examined soil profiles[21].

Boron content of soils ranged from 4 to 630 mg • kg^{-1} in soils of India[21]. Total B content of some podzol soils from eastern Canada ranged from 70 to 116 mg • kg^{-1}[23]. A study conducted on 108 soil samples showed a positive correlation ($r=0.39$) between total and hot-water soluble B suggesting that total B can be used to some extent as an index of availability[23].

Of all the micronutrients, total Mo is in the smallest amounts, ranging from 0.05 to 3.2 mg • kg^{-1} in soils of India[21]. In humid regions, the total Mo content in soils is about 2 mg • kg^{-1}[19]. Although there are no actual data available showing the relationship between total and available Mo in soil, the total soil Mo is an important reserve. Gupta[15] showed that soils containing very low quantities of Mo were not able to meet the Mo requirement of crops even when they were sufficiently limed. This was not the case on soils that contained higher total Mo. A summary of total micronutrients in soil as reported by various researchers is presented in Table 1.

Table 1 Total micronutrient content in soils

Nutrient	Content in soil			
	a	b	c	d
Boron, mg • kg^{-1}	10–100	50	4–630	
Manganese, mg • g^{-1}	0.05–5	2.5		
Zinc, mg • kg^{-1}	10–300	100		
Copper, mg • kg^{-1}	1–200	100		
Iron, mg • g^{-1}	5–100	25		
Molybdenum, mg • kg^{-1}	0.5–3.5	2		0.15–0.35

a: Bergeaux, 1966[20]; b: Giddens, 1964[19]; c: Chatterjee et al., 1976[21], Gupta, 1968[23]; d: Gupta, 1969[15].

3 Crops sensitive to micronutrient deficiencies

Crops in their response to various micronutrients vary considerably as mentioned in the previous section. For example, Mo is highly important for legumes because it is required for biological N-fixation, an activity carried out by root nodule bacteria (*Rhizobium*) in leguminous crops[24]. Absence of Mo results in poor growth and activity of root nodules. Specific micronutrient deficiencies in a variety of crops in various states of the U. S. A., are described by Sparr[25]. Corn is highly sensitive to Zn deficiency, which is one of the most important trace minerals in many countries[26,27]. Relative sensitivity of important crops to micronutrient deficiencies as summarized by Martens and Westermann[27] is presented in Table 2.

Table 2 Relative sensitivities of selected crops to micronutrient deficiencies

Crop	Sensitivity to micronutrient deficiencies					
	B	Cu	Fe	Mn	Mo	Zn
Alfalfa	H*	H	M	M	M	L
Barley	L	M	H	M	L	M
Bean	L	L	H	H	M	H
Cauliflower	H	M	H	M	H	—
Clover	M	M	—	M	M	L
Corn	L	M	M	M	L	H
Grass	L	L	H	M	L	L
Oats	L	M	M	H	L	L
Potato	L	L	—	H	L	M
Sorghum	L	M	H	H	L	H
Soybean	L	L	H	H	M	M
Sugarbeet	H	M	H	M	M	M
Turnip	H	M	—	M	M	—
Wheat	L	H	L	H	L	L

H* = High, M = Medium, L = Low.

Various degrees of sensitivity to micronutrients for a number of tropical crops have been summarized by Bennett[28]. A brief discussion on sensitivity to micronutrient deficiency in some crops as summarized by various researchers is reported in Table 3.

Table 3 Sensitivity to deficiency of micronutrients for a few crops

Crop	Sensitivity to deficiency for	Reference
Citrus	Fe, Zn, Mn, Cu, B, Cl and Mo	Wutscher and Smith, 1993[29]
Cotton	Mn, Zn, Fe and B	Cassman, 1993[30]
Peanuts	Fe, Zn, Mn, Cu, B and Mo	Smith et al., 1993[31]
Rice	Fe, Zn, Mn and Si	Wells et al., 1993[32]
Sugarcane	Fe, Zn, Mn, Cu, B, Cl, Mo and Si	Gascho et al., 1993[33]

4 Crop response to micronutrients

Micronutrient deficiencies are widespread in developing countries, which have much poorer soil resources than the fertile soils of Europe and North America[34]. Many of these areas lie in the humid tropics with extremely infertile, highly weathered, and/or highly leached soils, which are intensely deficient in nutrients. The rest of such soils are in the semiarid and areas adjacent to the latter, where alkaline and calcareous soil conditions severely limit the availability of micronutrients to plants[34].

Crop response to micronutrients is generally found in the form of increased crop yields and/or improved crop quality. The latter could be associated with physiological changes in the various parts of plants, e.g., as reported for B by Shelp[35] and for Mo by Srivastava[24]. Responses to micronutrients differ with crops, e.g., cereals are more sensitive to Cu than other crops[6,10,36]. This section will limit discussion to crop yield responses.

Molybdenum Crop responses to Mo occur on a variety of crops[8,37]. For legumes, which are most sensitive, there are genotypes and species differences in response to Mo. A number of factors, e.g., soil pH, can greatly affect crop responses to Mo[15]. A brief summary of this relationship is reported in Table 4.

In addition to legumes, plants belonging to *Brassicae* family, rice (*Oryza sativa*), peas (*Pisum sativum*), peanuts (*Arachis hypogaea* L.), soybeans (*Glycine max* (L.) Merr.), and wheat (*Triticum aestivum* L.) are also responsive to Mo[8].

Boron Forage legumes in general are more susceptible to B deficiency than grasses. Other crops, which respond to B, include those belonging to the Brassicae family, cotton (*Gossypium hirsutum*), soybeans, and peanuts[38]. Grasses and most cereals are the least responsive to B. A summary of the degree of yield response to B on a few crops is reported in Table 5. For a detailed reading on this topic, the reader is referred to a recent article by Gupta[45].

Copper Response to Cu has been found on a wide variety of cereals such as wheat, corn (*Zea mays* L.), rice, oats (*Avena sativa* L.), and barley (*Hordeum vulgare* L.) in U.S.A., India, Kenya, U.K., and Australia as reviewed by Graham and Nambiar[46]. Cereal crops are by far the most sensitive to Cu, although Cu deficiencies have also been reported for a wide range of agricultural crops, including vegetables and fruits grown on soils low in available Cu[36]. Penney et al.[10] reported that crop yield responses to Cu are wide spread in Australia, N.Z., and U.S.A. They are also most common in the wheat producing areas of Australia, whereas in the Central Plains region of North America, significant cereal yield responses to Cu have been reported.

Zinc Globally, Zn deficiency is the most important problem, particularly in alkaline-calcareous soils[47,48]. Factors that induce Zn deficiency include soil pH, soil calcareousness, low soil organic matter, sandy soil texture, eroded soils, and accentuated Zn mining by high yielding varieties[49].

Zinc deficiencies mainly occur on sandy soils, on soils with a pH$>$6.0, and hence, continuous fertilization without supplementation of Zn may induce Zn deficiencies. It is mobile at slightly acidic conditions and is immobilized in alkaline soils. Antagonism of zinc in soil, e.g., with Phosphorus (P), calcium (Ca), Fe, Cu, and nickel (Ni) has been reported, as summarized by Deckers and Steinnes[34].

Crop yield responses to Zn are wide spread throughout the world. In a study conducted in India, it was reported that cultivars, which exhibit greater efficiency for P, Fe, and Mn are relatively more susceptible to Zn deficiency[26].

Among the Zn responsive crops, rice has been shown to be sensitive to Zn with many reports of responses world wide over the past 30 years[32]. Corn is also highly responsive to Zn, and under Zn deficiency, corn yields can be greatly reduced[50]. They further reported that citrus [*Citrus sinensis* (L.) (Osbeck)] cotton, flax (*Linum usitatissimum* L.), onions (*Allium cepa* L.), and sorghum (*Sorghum bicolor* (L.) Moench) have also been found to be responsive to Zn. A report from India showed that green and black grams (*Cicer arietinum* L.) were highly responsive to Zn[51]. Kumar et al.[52] remarked that continued use of nitrogenous fertilizers during the last few decades has caused a wide-spread Zn deficiency particularly in light-textured soils. In the south-west of Western

Table 4 Crop yield response to Mo as influenced by liming on two soils

Crop	Soil pH	Sandy loam		Silty clay loam	
		No Mo	With Mo	No Mo	With Mo
Cauliflower yield, g/pot	5	0.1	0.3	0.3	1
	6	0.5	9	3.3	10.1
	6.5	1	9.7	12.3	13
Alfalfa yield, g/pot	5	0.3	0.3	1.2	1.2
	6	3.3	4.8	15.8	15.6
	6.5	1.7	5.3	19.6	15.3

Table 5 Crop yield response to B on a few crops

Crop	Country	Yield response	Reference
Alfalfa	New Zealand	9%-43%	Sherrell and Toxopeus, 1978[39]
	Canada	8%-32%	Gupta, 1984[40]
Black Gram	Thailand	40%-80%	Rerkasem et al., 1988[41]
Cotton	U. S. A. and China	13%-29%	Lancaster et al., 1962[42]; Summarized by Shorrocks, 1987[43]
Soybeans	U. S. A.	Inconsistent	Touchton et al., 1980[44]
Sunflower	Thailand	50%	Rerkasem et al., 1988[41]

Australia, large cereal grain yield responses have been reported[9]. In citrus, Zn responses occur in all the places it is grown[29]. Under Zn deficiency, fruits are small, misshapen, and bleached to whitish color.

Manganese Manganese responses are most likely to occur on high organic soils and in high-pH, calcareous, or sandy soils[53]. Yield responses to Mn are widespread on soybeans. Manganese deficiency has been frequently detected in soybeans in the Atlantic Coastal Plains of the United States[54]. In some regions, yield responses to Mn have occurred on oats[55]. Sugar beets have also been found to respond to Mn with increased beet root yield and increased sugar content[11]. In studies conducted in the U. K., responses to Mn on beets were slight and only on soils with pH higher than 7.0[56].

Manganese deficiency in citrus is widespread but often is only of transient occurrence. Like the other heavy metals, Mn deficiency occurs only in young, enlarging leaves[29]; only persistent and severe pattern development of the foliage requires correction.

Silicon Although the essentiality of silicon (Si) has not been proven, Si application on organic soils has increased Si concentration in leaves and rice grain yield[57]. Silicon response in rice also shows a increased resistance to disease, improvement in water use efficiency, and increased grain yields[58]. Silicon deficiency results in premature senescence and poor tillering in sugarcane[33]. Sometimes the sugar yield increases due to Si in sugarcane (*Saccharum officinarum* L.) have been very large in studies conducted by Fox et al[59].

Sodium Sodium (Na) is essential for the growth of animals and some plant species[60]. According to Lehr[61], plant species that were benefited most from Na, when adequate K is supplied, are celery (*Apium graveolens* L.), sugar beet, swiss chard (*Beta vulgaris* subsp. cicla (L.) Koch), and turnips (*Brassica rapa* L.). In addition to dry matter yield response, there have been positive effects of Na on sugar concentration in sugar beets[62] and in the fiber quality of flax[63].

5 Significance of plant part sampled in crop nutrition

The precision of modern analytical methods is such that even microquantities of most micronutrients in plants can be detected accurately. Studies characterizing the nutrient content in various parts of plants can assist in evaluating the nutrient status of crops. The plant parts that accumulate the highest concentration of nutrients during the active metabolic stage of growth are often best suited for sampling to determine the nutrient status of crops. The higher the capacity for a plant part to accumulate a nutrient, the greater would be the differences in its nutrient concentration in response to varying rates of fertilization. This has been shown to be the case, e. g., for B where, in response to added B, the leaves accumulated 10 times more B than did the roots[64].

The B concentrations in leaves and roots with and without applied B are shown for rutabaga (*Brassica napobrassica* L.) in Table 6. Results clearly show that roots are a poor indicator of B status since differences between the treated and untreated plants are extremely small. This knowledge of plant parts, which accumulate the highest concentration, should prove to be an useful criterion in delineating the levels of nutrients from sufficiency to toxicity.

Table 6 Boron concentration in rutabagas leaves and roots with and without applied B in three different soils

Soil	B rate, kg • ha^{-1}	Leaves	Roots
		B, mg • kg^{-1}	
Sandy loam	0	8	13
	2	146	18
Sandy clay loam	0	7	10
	2	78	16
Silty clay loam	0	35	14
	2	108	19

For most crops, the above ground vegetative tissues are sampled to determine the nutrient status. Micronutrient concentration in plant parts for a variety of crops have been reported by Gupta[65,66]. Studies have shown that leaves generally contain higher concentration of most micronutrients than, e. g. , stem[66] as shown in Table 7.

Table 7 Boron, molybdenum, copper, and zinc concentration in leaves and stems in a few crops

Crop	Leaves	Stems	Leaves	Stems
	B, mg • kg^{-1}		Mo, mg • kg^{-1}	
Alfalfa	25	14	0.28	0.15
Red Clover	23	16	0.12	0.15
Cauliflower	36	19	1.65	0.98
Broccoli	36	37	3.76	1.76
	Cu, mg • kg^{-1}		Zn, mg • kg^{-1}	
Alfalfa	9.9	9.6	27	13
Red Clover	17.8	9.9	43	16
Cauliflower	5.2	3.8	49	34
Broccoli	6.6	5.3	54	37

It has been reported that with maturity, the Mo concentration in leaves and stems decreases[67]. It is therefore imperative that the stage of a crop must be considered as an important factor when interpreting plant analytical data for Mo and possibly for other micronutrients as well. It is also important to be consistent with the plant sampling technique used in the field, as well as with the plant part sampled. Results as reported in this section suggest that whenever possible, leaves should be sampled to characterize the micronutrient status of crops. However, more work is needed on the physiology of translocation to establish the quantitative patterns of redistribution of these nutrients in various plants in response to micronutrient fertilization.

6 Micronutrient deficiency and toxicity in crops

Micronutrient deficiencies in various crops have increased principally because of intensive cropping, liming, leaching through precipitation, modern high yielding cultivars, and loss of top soil from erosion. Decreased use of plant residues and animal manures and use of high analysis fertilizers are also some of the main factors resulting in micronutrient deficiencies.

Deficiency symptoms for most micronutrients appear on the young leaves at the top of the plant because most micronutrients are not readily translocated. Molybdenum is an exception in that it is readily translocated, and its deficiency symptoms generally appear on the whole plant[68]. Toxicity symptoms for most micronutrients appear on the older leaves of the plant, which is very striking for B[69]. Molybdenum toxicity is generally marked by chlorosis, yellowing, and other forms of leaf discoloration. This section will present some examples for a number of crops. Micronutrient toxicity levels in crops have been summarized in Table 8.

Table 8 Micronutrient toxicity levels in crops

Element	Toxic levels* in plants/(mg • kg^{-1})
Boron	10–50
	>200 for tolerant crops
Copper	10–70
Manganese	400–7,000
Molybdenum	100–1,000
Zinc	95–340
Nickel	8–147

* Associated with toxicity symptoms and/or reduced yield.

Boron Boron deficiency in corn is seen on the youngest leaves as white irregularly shaped spots scattered between the veins. It can curtail development of the corn ear[70]. In peanuts, it results in hollow-heart in kernels[41]. Deficiency results in rough and netted rutabaga roots, which exhibit hollow-heart upon cutting[71]. In soybeans, it results in necrosis of the apical growing point and young growth[72]. In the case of cotton, the terminal bud often dies[73]. Boron deficiency in sugarcane results in distorted leaves, severely burned leaf tips, and brittle and necrotic leaves[33]. In citrus, it results in short internodes, thickened leaves, and corky venation[29].

Boron toxicity symptoms in most crops are marked by burned edges on the older leaves[69]. In peanuts, B toxicity causes marginal leaflet chlorosis, which soon progresses to a marginal necrosis[74]. Boron toxicity in citrus can result in yellowing of the leaf tips and mottling followed by premature drop[29]. In sugarcane, chlorosis of tips and margins spreads on young leaf blades and extends to older and chlorotic tissues, which quickly became necrotic. Deficient, sufficient, and toxic concentrations of B in crops are described by Gupta[75].

For a detailed description on topics related to boron, e. g. , its reaction in soils, its role in plant physiology, diagnosis of its deficiency symptoms, methods, and rates of its application, the reader is directed to a recent publication on a practical guide to boron[76].

Molybdenum Molybdenum plays a biochemical role in animals and man in enzymes such as aldehyde oxidase and xanthine oxidase[77].

Symptoms associated with Mo deficiency in plants are often closely related to nitrogen metabolism because of its requirement for nitrogenase activity and nitrogen fixation. Molybdenum deficiency in Brassicae family crops generally include chlorosis, cupped leaves, and rolling or upward curling of leaves[68]. In corn, the internodes are short, leaf area is reduced, and leaves appear chlorotic[72]. Molybdenum deficiency in melons (*Cucumis melon* L.) results in poor and delayed flowering and reduced viability of pollen grains, leading to reduction in the formation of fruit[78]. In soybeans, symptoms resemble those of nitrogen deficiency and likely are caused by reduced nitrogen utilization.

In sugarcane, Mo deficiency results in dieback of old leaves, and leaf blades are uniformly light green to yellow[33]. Symptoms of Mo deficiency in citrus first appear as a “yellow spot”, which develops on fully matured leaves. Spots occur at random on the leaf, turn reddish brown, and leaves drop prematurely[29].

Molybdenum toxicity in crops is not common and is found only when unusually high concentrations of Mo are present. In soybeans, high rates of Mo application can be detrimental to *Rhizobia* in the seed inoculum[79]. Symptoms of excess Mo in sorghum leaves appear as a dark violet coloration of the whole lamina and are distinguishable from the symptoms of P deficiency, which results in dark green leaves with overtones of dark red coloration[80]. High concentrations of Mo in feed crops can cause toxicity in animals as discussed by Pasricha et al[81]. Deficient, sufficient, and toxic concentrations of Mo in crops are described by Gupta[82].

Copper Copper deficiency in crops is widespread and occurs all over the world, particularly on soils with high pH, high organic carbon content, and excessive drainage conditions. Copper deficiency and toxicity symptoms have been described in detail for a variety of crops[36]. Cereals generally suffer due to a lack of Cu. Even under mild or moderate Cu deficiency, e. g. , barley and oats may not show the characteristic symptoms and yet may suffer severe loss of grain yield[46]. Under Cu deficiency, wheat heads are small and 10 to 14 days late in emerging[83]. Copper deficiency in sorghum appears first on young leaves within the whorl and on young mature leaves, and plants are stunted and growth is depressed[80].

In sugarcane, Cu deficiency results in bleached leaves, which become paper thin and rolled when deficiency is severe[33]. Symptoms of Cu deficiency in citrus include dieback of twigs, narrow elongated leaves in new shoots, brown lesions on fruits, and fruit drop[29].

Copper toxicity is generally not common even when applied in large quantities. During early stages of Cu toxicity, reduced growth of crops is evident. In addition, Cu toxicity causes reduced branching, thickening, and abnormally dark coloration in the rootlets of plants[84]. In sorghum, Cu toxicity turns interveinal tissue lighter similar to Fe deficiency with red streaks along the margins[80]. Copper toxicity in citrus damages the root system and leads to drought symptoms in trees with sparse foliage and very small leaves[29].

Iron Iron deficiency in citrus is common. The common symptoms in citrus are very distinct and consist of yellow leaves with green mid rib and lateral veins[29]. These symptoms occur only on young leaves. In rice, Fe deficiency occurs on neutral to alkaline soils. Symptoms include chlorotic and bleached to white newly emerging leaves[32]. Likewise, in sorghum, Fe deficiency is also pH related and is often called as lime-induced chlorosis when grown on alkaline calcareous soils. Iron deficiency symptoms first appear on young leaves with long yellow streaks in the interveinal tissues[32]. In sugarcane, Fe deficiency results in distorted and necrotic leaf blades and interveinal chlorosis occurs from tip to the base of the leaves[33].

A direct Fe toxicity from a general soil application of Fe fertilizer would not be expected because of the relatively rapid conversion of soluble Fe to insoluble Fe compounds in soil systems[27]. Iron toxicity can be a problem for sorghum grown on some acid soils. Excess Fe causes leaves to turn light with blackish, straw-colored lesions at the margin[80]. In soybeans, Fe toxicity symptoms are very similar to those of Mn except the Fe-toxic leaves are less crinkled than Mn-toxic leaves[85].

Manganese Manganese deficiency generally occurs on high pH soils. In sorghum, Mn deficiency symptoms normally appear first on middle to upper leaves as distinct lesions in the interveinal tissue[80]. In cotton, Mn deficiency results in cupping and interveinal clorosis on younger leaves, and there occurs a delay in the appearance of first flower[30]. Symptoms of Mn deficiency in sugarcane include interveinal chlorosis, which occurs from the tip toward the middle of the leaf[33]. In sugarbeets, symptoms are not readily distinguishable at times from Cu or Fe deficiencies. With severity of symptoms, leaf blades of Mn deficient plants gradually fade from green to a uniform yellow with a metallic gray luster[86].

Manganese toxicity is found in crops growing on strong acid soils[87,88] and on soils with high levels of water soluble or salt extractable Mn[89]. Manganese availability to crops is enhanced by reducing conditions in poorly aerated or submerged soils. Consequently, barley adapted to a well drained soil environment suffers due to excessive Mn and shows as severe incidence of brown spotting of older leaves[90]. Toxicity of Mn in sorghum consists of dark green older leaves with large number of small dark reddish purple spots all over the leaf[80].

Zinc Zinc deficiencies are more prevalent in crops grown on high pH, organic and sandy-textured soils than on heavier soils. Zinc deficiency in corn exhibits a white coloration in the top leaf also known as "white bud"[50]. Corn plants are stunted and internodes are short. Zinc deficient soybean plants have stunted stems and chlorotic interveinal areas on younger leaves[91]. Typical symptoms of Zn deficiency in sugarcane include veinal chlorosis at the base of young leaf blades and leaves are small and nonsymmetrical[33]. In citrus, Zn deficiency is very common and produces a distinctive yellow mottle on leaves that are reduced in size[29]. Continued stress leads to defoliation and twig dieback and fruits are small and white to bleached.

Maize (corn) is a poor accumulator of Zn, especially the higher yielding hybrids[92]. This is an important negative factor in a region such as southern Africa, where corn is the main staple food for the majority of the population.

Most crops are highly tolerant to excess Zn. For example, Zn applications of up to 300 $\mu g \cdot g^{-1}$ did not cause reduction in spring wheat yield[93]. They further reported that even at very high Zn application rates of 1000 $\mu g \cdot g^{-1}$, wheat yield was reduced by 40%. Potential phytotoxicity from excess Zn applications exists because only small amounts of Zn leach and because reversion of applied Zn to unavailable forms is relatively slow in soils[94]. Recent studies by Gupta and Kalra[45] showed that Zn and Cu applications as high as 50 and 25 kg/ha, respectively, for two years in succession did not cause any phytotoxicity in wheat and barley.

Iodine The iodine (I) content of surface soils decreases rapidly with increasing distance from the sea[95]. High pH and higher Ca contents in soils reduce its bioavailability and decreases its uptake by plants[96]. Generally, iodine deficiencies occur in areas where the iodine containing top soil has been removed either by glacial movement or soil erosion. Leaching of soil by percolation or by seasonal flooding may also lead to iodine deficiencies, e.g., in the North American central plains, the lowlands of Central Africa, the mountainous zones of China, and the Po plains in Italy[97].

Rare Elements The rare elements include 14 lanthanides (atomic number 57 through 71), and their average content in the earth's crust varies from 66 μg Nd g^{-1} and 35 μg La g^{-1} to 0.5 μg Tm g^{-1}[98]. It was further stated that under certain conditions, low concentrations of at least some rare elements appear to favor plant growth productivity, but the physiological mechanisms are still not understood[98].

7 Heavy metal toxicities

Heavy metals in animal manures and sewage sludge (biosolids) may accumulate in soil with repeated fertilizer applications[99]. Cadmium is the heavy metal of most concern because it may affect human health. Other heavy metals of possible significance are arsenic (As), chromium (Cr), lead (Pb), mercury (Hg), and nickel (Ni).

Generally, cadmium (Cd) is not toxic to plants. However, it is a heavy metal of significant concern because it can accumulate to levels in plants, which can be toxic to animals and livestock. Studies by Dudka et al.[93] showed that Cd concentrations, 25 times higher than control, in wheat were not harmful. However, the resulting grain could be toxic to livestock. Field studies by Holmgren et al.[100] showed little evidence of significant accumulation of Cd or Pb in cropland soils, although Zn and specially Cu have accumulated from normal agricultural practices. Certain leafy vegetables can absorb significant amounts of Cd, Cr, Ni, and Pb, whereas these absorbed metals are usually poorly translocated to cereal grains[101].

Nickel toxicity occurs on soils to which large quantities of Ni have been added in wastes, e. g. , in the form of sewage and sewage sludge and in crops growing near Ni mines and smelters. Crops, e. g. , oats grown on ultrabasic rocks, rich in Ni, showed Ni toxicity[102]. Symptoms of Ni toxicity in crops include chlorosis and other symptoms specific to plant species[103].

Like Ni, toxic levels of chromium (Cr) are found in soils amended with Cr-rich sewage sludge or wastes from the dyeing and tanning industry[104]. Toxicity symptoms of Cr include restriction in the growth of roots and shoots and chlorosis in leaves[105].

Plant species differ in their toleration to As. For example, in a study by Carbonell-Barrachina[106], it was found that arsenate was toxic to tomatoes and beans; however, tomato plants were more tolerant to As pollution than bean plants. Bean plants exhibited symptoms of As toxicity and plants treated with As died after 36 days. In tomatoes, As exposure resulted in a significant dry mass production, but tissue chlorosis or necrosis were not observed.

A range of toxicity values for micronutrients as summarized by Gupta and Gupta[17] is presented in Table 8.

8 Micronutrients in animal nutrition

Zinc is an important trace element and fulfills many biochemical functions in animal metabolism. Zinc binding compounds as referred by Scherz and Kirchhoff[107] are of particular interest, in order to gain insight in the functions and bioavailability of Zn to animal and plant food tissues. Like many diseases in man, several disease conditions in animals show a definite geographical distribution. Among those, disorders related to soil chemistry constitute a significant part. Deficiencies of essential trace elements are of main concern in a global context[108].

Essential micronutrients: Fe, Zn, Cu, Mn, Se, I, cobalt (Co), and Mo are required in amounts $\leqslant 100\ \mathrm{mg \cdot kg^{-1}}$ in dry matter. Most of these with the exception of Mo are deficient in some natural feed ingredients, necessitating their supplementation. Iron deficiency anemia is of universal concern particularly in new born pigs[109]. The blood hemoglobin concentration has been considered as a simple and reliable index of pig Fe status[110]. Signs of chronic Fe toxicosis are reduced growth and reduced feed intake and efficiency.

Zinc deficiency is likely to present a practical problem with nonruminants but marginal deficiency may occur in grazing sheep and cattle as reviewed by Miller et al[3]. Zinc deficiency is characterized by retardation, cessation of growth, and reproductive problems[111]. Copper deficiency occurs naturally in grazing livestock but not in poultry or pigs fed typical corn-soybean meal diets. Severe Cu-deficiency symptoms include diarrhea, weight loss, rough hair coat, fragile bones, and stiff joints. All Cu-deficient species manifest anemia.

Selenium deficiencies in humans and animals are widespread throughout the world; whereas Se toxicities occur in smaller pockets in various regions of the world. In areas where soil Se is low and people live mainly from locally grown food, such as in parts of China, severe problems associated with Se deficiency may occur.

The first disease associated with Se deficiency was Kashin-Beck disease, which was discovered in 1849 in China[96]. It occurs in the mountains and hills of central China extending across the country from north-east to south-west[112]. It also occurs in eastern Siberia and North Korea. It is interesting to note that the Se content of most cereals is deficient with the exception of rice, which appears to concentrate Se from the environment. People on a high rice diet clearly showed less Se deficiency symptoms compared with people with other eating habits. Zhu[113] refers to the supplementation of Se via salt and tablets as early as 1974 in China. Since 1984, Se has been added systematically to the human diet in China via kitchen salt or by distribution of Se tablets to the people. These additions have resulted in a spectacular drop of the Keshan disease symptom.

A major sign of Se deficiency in all livestock, especially the young, is white muscle disease or nutritional muscular dystrophy[111]. This myopathy is associated with excessive peroxidation of lipids, resulting in chalky white striations, necrosis, and fibrosis of myofibrils. In swine, it includes hepatosis dietetica and mulberry heart disease. An excellent description on the role of trace elements in animal nutrition is presented by Miller et al[3].

Trace elements play important roles in the development of embryo and fetus during pregnancy in animals. A study by Hostetler et al. [114] showed that levels of Zn, Cu, and Mn are among the trace elements, which were several-fold greater in the conceptive tissue than in the other reproductive tissues, indicating that the conceptive tissue preferentially accumulates these minerals, an action that may be important for conceptive development, growth, and survival. These results indicate that these minerals may lead to development of specific programs to increase the number and health of offspring at parturition, thereby allowing further improvements in production efficiency in livestock industry.

9 Micronutrient sufficiency levels in feed crops for yield vs. animal requirement

Often, when one talks about sufficiency levels of nutrients in crops, there is a range in values rather than one definite number that could be considered "critical". Therefore, the term sufficient will be used wherever possible. When describing sufficient levels in forages, consideration must be given to the animals since the latter will consume the feed crops.

So far B has not been proven essential for animals and therefore its levels only in forages will be considered. Generally, 20 to 40 mg B kg^{-1} in the whole tops of alfalfa and red clover have been considered to be sufficient[16,115]. Grasses generally require less B than forage legumes, and hence, their sufficiency levels are also low. For example, pasture grasses, rye grass, and timothy containing as low as 3 to 10 mg B kg^{-1} are considered sufficient as summarized in Table 9.

Molybdenum deficiency in animals is apparently relatively rare and is usually produced by feeding its antagonist, tungsten, in amounts 1000-fold greater than Mo[116]. However, Mo deficiency occurs occasionally as reported by Anke et al.[117] in goats when ratios contain 0.024 mg Mo kg^{-1}. This level is unusually small and does not occur frequently. Like B, forage legumes are more responsive to Mo than grasses. Sufficient levels of Mo in forages are lower than for most other micronutrients. Often they are less than 1.0 mg • kg^{-1}. Sufficiency levels of Mo in alfalfa and red clover range between 0.2–0.5 mg • kg^{-1} and in timothy and tropical and temperate pastures as low as 0.1[82]. Sufficiency levels vary depending upon the age and part of the plant sampled. Detailed sufficiency levels in various forage species are described in Table 9.

The requirement for Cu by most of the animals is low when compared with the requirement for most other minerals. As evident from Table 9, sufficiency levels of Cu for cattle and sheep at 6 to 10 mg • kg^{-1} are low, and most forages appear to contain sufficient Cu. Levels of Cu that are sufficient for forages are also adequate for cattle and sheep. However, the requirement of Cu for pigs at 50 to 60 mg • kg^{-1} and chickens at 60 to 80[3,121] is higher than 8 to 35 mg Cu kg^{-1}, which is considered sufficient for most forages (Table 9). Researchers from South Australia reported that Cu concentrations of less than 4 mg • kg^{-1} indicate deficiency in subterranean clover[6]. However, they concluded that Cu deficiency may occur in livestock even when Cu concentrations in pastures are 10 mg • kg^{-1}.

It is important to consider feed crops Mo level when discussing Cu sufficiency for livestock. Animals grazing on pastures high in Mo could develop Cu deficiency in spite of the fact that the Cu concentration in forages is adequate for maximum dry matter production. This is considered as Mo induced Cu deficiency[129]. In such cases, high Cu supplementation with sulfates may be necessary to immobilize Mo[130]. A survey on Cu and Mo concentrations in forages and beef cattle liver, in the state of Mato Grosso, Brazil, showed that high levels of Mo and Cu concentrations of less than 5 mg • kg^{-1} were found in forages. However, the levels of Cu in the liver were normal for animals because of Cu supplementation in the salt mixture[131]. Ratios of Cu:Mo in the range of 2∶1 to 7∶1 have been reported to be critical but Cu deficiency in animals does not occur if feed intakes of Cu are more than 5 mg • kg^{-1}[5].

Studies conducted in Prince Edward Island (P. E. I.) showed that Mn levels as low as 31 to 34 mg • kg^{-1} were in the crop sufficiency range[124]. These Mn levels for poultry and ruminants are not sufficient whose requirements are higher at 50 mg • kg^{-1}, e. g., for ruminants. The recommended level for ruminants is 50 but it cannot be given with any certainty.

Field studies in P. E. I., eastern Canada showed that Zn levels as low as 12 to 16 mg • kg^{-1} in alfalfa and rye grass were sufficient for maximum dry matter yield[126]. However, these levels are far short of the sufficiency levels of 50 to 100 for pigs[110] and of 50 mg • kg^{-1} for dairy cows[119]. Zinc is an indispensable component of a number of enzymes or other proteins in animals[132]. It is essential for maintaining normal growth, reproduction, and lactation performance[109]. Forages in the north eastern part of North America do not contain enough Zn to meet the recommended Zn allowance at 40 mg • kg^{-1} for dairy cattle[133]. In the State of

Table 9 Sufficiency levels of micronutrients in livestock feeds and animals

Nutrient	Sufficiency Levels, mg · kg^{-1}	
	Forages	Animals
* Copper	Alfalfa 8-12 (Gupta, 1989[118])	Cattle 4-10 (NRC, 1988[119])
	Timothy 5-8 (Gupta, 1989[118])	Sheep 6-10 (Underwood, 1981[111])
	Red Clover 8-17 (Neubert et al., 1970[120])	Pigs (post weaning) 60(NRC, 1988[110])
	Pasture grasses 5-12 (Neubert et al., 1970[120])	Pigs when fed high Cu diet 50 (Suttle and Mills, 1966[121])
Iron	Alfalfa 35-50; Barley & Oats 19-24 (Gupta, 1991[122])	21 mg** Fe/kg body weight (baby pigs) (ARC, 1981[123])
	Timothy 23-47 (Gupta, 1991[122])	Leghorn chicken 60-80; Broiler chicks 80 (Miller et al., 1991[3])
Manganese	Alfalfa 31 to 49; Timothy 34 to 53; Wheat and Oats 22-26 (Gupta, 1986[124]);	Poultry and chicks 50 (Underwood, 1981[111]); Ruminants 40 (NRC, 1988[119])
Zinc	Crotolana anagryoides 10 (Widdowson, 1966[125]); Alfalfa 16-28; Ryegrass 12 to 22 (Gupta, 1989[126])	Pigs at various stages of growth 50 to 100 (NRC, 1988[110]); Dairy calves, dairy cows and bulls 50 (NRC, 1988[119]); Swine at various growth stage 35 to 65 (NRC, 1984[127])
Cobalt	Alfalfa 0.030-0.42; Timothy. 012-0.24; Barley and Oats 11-12 (Gupta, 1993[69])	Ruminants 0.1 mg · kg^{-1} (Smith, 1987[128]); (NRC, 1988[119]); >0.07 for sheep, >0.04 for cattle (ARC, 1965)

* Copper concentrations in relation to Mo and S in the ration; ** Based on body weight, all other values are in forage dry matter.

Mato Grosso, Brazil, low levels of Zn in the soil, forage (less than 30 mg · kg^{-1}), and beef cattle liver were found by Sousa et al. [134] in a survey on several farms. Hutton[135] mentioned that at the beginning of the 70's, the fotossensibilization in young animals grazing *Brachiaria decumbens* was a serious problem in Central Brazil and that the problem was linked to low levels of Zn in forage.

Cobalt concentrations as low as 0.022 and 0.012 mg · kg^{-1} in alfalfa and timothy, respectively, were sufficient for maximum dry matter yields[69]. Generally, the requirement of Co for crops is very low. Cobalt concentrations found adequate for forages are inadequate for a variety of animals. As summarized in Table 9, the Co requirement for various class of livestock is higher and ranges from 0.04 to 0.10 mg · kg^{-1} in the feed.

In the semiarid southern region of Puerto Rico, Mn, Cu, Co, and Se levels in pastures have been found to be below the recommended levels for grazing ruminants[136]. Their research indicates the need for livestock supplementation even under conditions of high pasture fertilization with NPK. Selenium is a trace mineral, which is not required by crops, and maximum forage yields can be obtained on soils with amounts of Se as low as 0.01 mg Se kg^{-1}. However, if animals are fed forages with less than 0.1 mg Se kg^{-1}, they could suffer from serious physical disorders[137].

10 Conclusions

This presentation includes a number of topics related to micronutrients. There is a great deal of information now available on crop responses to these nutrients and symptoms of deficiency and toxicity in various crops. More information is necessary on the significance of total micronutrients in soil in relation to the plant availability of these nutrients. Further research is needed to evaluate plant nutrient contents in feed crops as they relate to livestock. Nutrient sampling of the appropriate part of the plant and stage of growth for sampling crops should be standardized.

Data concerning the geographical distribution of micronutrients in the environment are essential for interdisciplinary, epidemiological studies conducted to confirm or refute association between animal and human diseases and the geochemical environment. Future crop varieties should be screened for susceptibility to micronutrient deficiencies. Research is required to assess the influence of agricultural and industrial activities on the environmental distribution of trace elements.

Studies on the micronutrients nutrition of crops should be conducted in conjunction with animal nutrition. Plant and soil data for micronutrients should be obtained to delineate areas of sufficiency and deficiency.

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