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Review Article

Weather - Micronutrient Interactions in Soil and Plants– A Critical Review

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Abstract

Agricultural and natural ecosystems are characterized by sub-optimal availability of mineral nutrients. Mineral deficiencies are probably have the complex and poorly understood relation with the global climate change variables. Climate change variables can affect soil nutrient availability as well as plant nutrient contents by affecting soil moisture, soil temperature and carbon dioxide, soil microbial activity and plant growth. Micronutrient deficiencies are becoming more severe due to the high nutrient demand from the exhaustive and unfair agricultural practices, coupled with the changing weather patterns. We know that chemical factors are more vital limitations to plant growth than physical factors on a global basis. The present review covers the impact of various climatic factors on the availability of micronutrients in soil and plant.

Keywords: Weather, change, Micronutrient, Soil temperature, Soil moisture, CO_2, Light

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Introduction

Introduction The world's weather pattern is increasingly erratic and unpredictable, fluctuating from warm days to cool days within the same season. Weather factors can affect soil nutrient availability as well as plant nutrient contents by affecting soil moisture, soil biological activity and plant growth. Deficiency of one or more micronutrients may reduce the quality and yield of the crop products, but the susceptibility to deficiency may vary with the cultivars or species. Among the essential elements, eight trace elements viz., zinc (Zn), iron (Fe), boron (B), copper (Cu), manganese (Mn), molybdenum (Mo), chlorine (Cl) and nickel (Ni) too are influenced by weather factors. These are as important as the major nutrients in plant nourishment but the requirements are far lower than the macro elements. Micronutrient deficiencies are prevalent in the recent past, due to increased nutrient requirement from the more intensive cropping systems without fewer replacements. Many authors have reported the enhanced crop yields owing to the addition of micronutrients elsewhere in the globe [1] (**Table 1**).

Nutrient concentrations vary between soil horizons and also with the soil chemistry which may vary in time depending on the temperature (air and soil) and soil moisture. A large amount of the terrestrial plant life is sustained by weathered soils with various combinations of low P, low Ca, Al toxicity, and Mn toxicity [2]. While high visible light intensity as well as excessive UV light can trigger photo-inhibition leading to photo-oxidative stress, mostly along with other environmental stresses [3, 4] which may guide to foliar nutrient disparities like nutrient deficiencies and impair plant productivity.

It was reported that soil temperature has obvious effects on root attributes like growth, morphology, respiration, and longevity and membrane fluidity to control the nutrient acquisition efficiency in plants [5]. In the current scenario, climate change and changing regional microclimates are getting more magnitude in terms soil fertility and agricultural production.

Table 1 The micronutrient levels limiting the crop yields in alfalfa, corn and soybean [1]

Micronutrient	13.4 t alfalfa	9.4 t corn	4.0 t soybean
B	0.33	0.18	0.11
Cu	0.07	0.11	0.11
Fe	2.02	2.13	1.90
Mn	0.67	0.33	0.67
Mo	0.02	0.01	0.01
Zn	0.27	0.30	0.22

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Micronutrient deficiencies: World scenario

Soil micronutrient deficiencies not only decline the crop productivity, but also lower the micronutrient content in plant food and hence harmfully affect human health and welfare [6]. Worldwide, zinc deficiency (**Figure 1**)is a well-known determinant disturbing the productivity of staple crops including maize, rice and wheat followed by boron. Notwithstanding to this fact, dicotyledonous species are found to be more susceptible to boron (B) than graminaceous species. Deficiency of iron is region specific, particularly in a Mediterranean weather and calcareous soils followed by copper (Cu). Scattered incidence of manganese (Mn) as well as molybdenum (Mo) deficiencies is also reported. Distinct symptoms are exhibited (**Table 2**) when severe micronutrient deficiencies occur. However, hidden deficiencies are also widespread. Soil tests as well as plant analyses are exceptional analytical tools to check the micronutrient status (**Table 3**) of soils and crops. Sometimes it may not be true that a high concentration of a particular micronutrient in soil will enough for the crop demand. That means, soil conditions ought to determine the nutrient availability. Although, micronutrient shortfalls are widespread, at various scales, soil conditions, weather, crop genotype and management, decide their occurrence. Among the weather factors both temperature (soil and atmosphere) as well as soil moisture play a predominant role in availability in different soils. Weather change-induced alteration in soil-water content can also seriously affect the accessibility and uptake dynamics of essential nutrients by the plants.

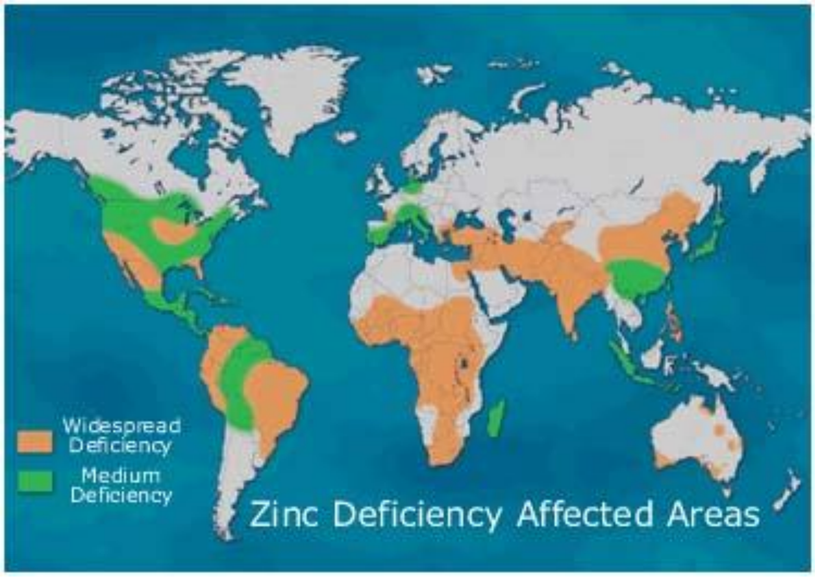

Figure 1 Zinc deficient soils [7]

Table 2 Micronutrient functions and deficiency symptoms in plants

Element	Major functions	General DeficiencySymptoms
Fe	Component of enzyme, Essential for chlorophyll synthesis, photosynthesis.	Interveinal Chlorosis in new leaves
Mn	Chloroplast production, co-factor in many plant reactions, activates enzymes.	Interveinal Chlorosis in young leaves.
Zn	Component of many enzymes, essential for plant hormone balance and auxin activity.	Stunted growth, reduced internodal length, young leaves are smaller than normal.
Cu	Component of enzymes, involved in photosynthesis	Overall chlorosis, leaf tip die back and tips are twisted, loss of turgor in young leaves
B	Important in sugar transport, cell division and amino acid production	General chlorosis, death of growing point, deformed leaves with areas of discolouration.
Mo	Involved in nitrogen metabolism, essential in nitrogen fixation by legumes	Pale leaves with interveinal and marginal chlorosis and necrosis.
Cl	Used in turgor regulation, disease resistance, fruit quality and photosynthesis	Chlorosis and wilting of young leaves. Deficiency rarely seen on crop plants in field.
Ni	Component of enzymes that involved in nitrogen metabolism and catalyze enzymes in nitrogen fixation.	Whole leaf necrosis along with necrotic leaf tips

There is a significant reduction (10-15 per cent) in protein concentration of main food crops like barley, wheat, soybean and potato, if atmospheric CO_2 attain 540-960 parts per million - a range predicted by the end of the present century.Besides, reduction in water dynamics in plant, would affect the uptake of micronutrients from the soil, through lowering concentrations of, zinc, iron, and manganese. Although micronutrient availability is linked to the quantity of micronutrient there in the soil few researches have revealed the CO_2-dependent stimulation in growth and enhanced requirements for macronutrients [8], however the varying demand for micronutrient is giving least importance. Even though the additional demand for macronutrients may partially be compensated through higher nutrient use efficiency [9,10], the growth stimulation may not be continued without sufficient nutrient supply.

Table 3 General interpretation of plant analysis for micronutrients (Dry weight basis)

Element	Symbol	Range of concentration (ppm)	Deficient Range (ppm)	Sufficient/Normal Range (ppm)	Excessive/Toxic Range (ppm)
Iron	Fe	20-600	<50	100-500	>500
Manganese	Mn	10-600	15-25	20-300	300-500
Zinc	Zn	10-250	10-20	27-150	100-400
Copper	Cu	2-50	2-5	5-30	20-100
Boron	B	0.2-800	5-30	10-200	50-200
Molybdenum	Mo	0.1-10	0.03-0.15	0.1-2.0	>100
Chlorine	Cl	10-80,000	<100	100-500	500-1000
Nickel	Ni	0.05-5	<0.05	0.05-5	>10

Zinc-Weather interactions

Amongst the micronutrient deficit in soil and plant, zinc deficiency is a worldwide deficiency problem noticed in several countries (Figure 1). Zinc is reported as one of the most limiting nutrients whose shortage is an extensively spread nutritional disorder in wetland rice [11]. Zinc is a vital element required for the proper growth and development of plants and its inadequate supply often lead to decreased crop production and excellence of the produce. According to Takkar and Walker [12] zinc deficiency is widespread in dry climatic condition mainly owed to low zinc solubility and high fixation. A shortage of zinc can results drops in effective photosynthesis by 50% - 70% depending on the crop species as well as the harshness of deficiency. This loss of yield of 40% or more in many zinc deficient soils have a major financial bang on the farmer owing to the lower return mainly due to yield loss. In case of rigorous farming where costly inputs like high yielding varieties, seed materials, agricultural chemicals and irrigation water are involved, crop failure and yield loss due to micronutrient deficiency is the most important impact on farmers income.

In soil, zinc is immobile and its deficiency may take place in different soil conditions like calcareous nature, sandy texture, high P condition and high erosion. The zinc present in soil solution is the only fraction accessible to plants. The most significant soil aspects which have an effect on the available zinc in soil solution comprise the total zinc content, organic matter content, pH, rhizosphere microbial activity, redox conditions, soil moisture, calcium carbonate concentration, amount of other micronutrients, macro - nutrients content, particularly phosphorus and weather parameters. As per reports zinc deficiency is the most prevalent micronutrient deficiencies in crops and results in severe decline in crop production [13]. Zinc deficiencies generally noticed in cool, wet environment in early spring time when there is slow root due to low soil temperature. Inadequately drained soils may also show zinc deficiency. The incidence of severe of zinc deficiency may accentuated by decrease in temperature and light fluctuations [14,15]. Under cool temperature the Zn deficiency will be further severe and it disappears as the temperature increases [16]. According to Najafi-Ghiri [17] soil temperature has a significant influence on Zn availability and the highest values were recorded in mesic temperature regime and lowest values were found in the thermic temperature regime.

Martin *et al*. [18] reported that zinc uptake in potato crops raised on a sandy loam textured soil augmented with increasing temperature. Elli *et al*. [19] reported that soil temperature below 16°C resulted in decreased zinc uptake in maize. This clearly tells that deficiency of zinc is linked to cool and wet weather. The reason for low availability of zinc during low temperatures are due to feebly developed root systems and reduced organic matter decomposition by microbes which would release zinc to the fresh crop. Since Zn is metabolically controlled the Zn adsorption might be increased as root temperature increase. At the same time the low root temperature is having detrimental effect on Zn accumulation. This may be owed to the lowered transport of Zn from roots to top as the root development is reduced under low temperature. It is also reported that compared to high temperature low temperature facilitate the antagonism between phosphorus and zinc [18]. Normal growth can be observed until a cool and wet period and when new growth comes it show chlorotic discolouration and occasionally appears unexpected colour contrast between green and yellow colour. Cold soils (usually accommodated with wet springs) can also influence soil zinc uptake even if levels are sufficient.

A study carried out by Najafi-Ghari [17] found that climatic condition has a considerable effect on Zn availability and the maximum value of Zn was found in soils having aquic condition. When the subsoil moisture is adequate to support growth, plants do not often show an increased incidence of Zn deficiency. Low soil moisture influences the movement of micronutrients in soil. The role of soil moisture is very critical in soils with low Zn availability. A study carried out by Bauer and Lindsay [20] reported that zinc uptake in rice was higher in hot and wet soil than in maize. Under water stressed conditions zinc nutrition will be adversely affected. So Zn deficiency will be a serious problem in rainfed agriculture. Also Zn application to inherently zinc deficient soils is useful in dropping phosphorus uptake and buildup in plants. This antagonistic effect of zinc and phosphorus may result in improved Zn bioavailability to human digestive system. Nambiar [21] showed that plants could absorb zinc from dried up soil via expelled mucilage but this absorption was only 40% as effective as uptake from wet soil. Mikkelsen and Brandon [22] reported that Zn shortage in rice is accentuated by flooding. Also elevated weekly evaporation, weekly relative humidity and built up rainfall decreased the absorption of zinc and in green tea stems [23]. A study carried out by Da Ge *et al*. [24] in maize under different moisture levels found that severe drought decreased the grain Zn content by 33 per cent against control. Velu *et al*. [25] reported that under circumstances of elevated temperature and drought stress there was higher grain Zn content in wheat grown in field condition. Under water logged circumstance the Zn concentration decreased remarkably in shoots of barley and wheat plants [26].

Abbas *et al*. [27] found that high CO_2 concentration supported increased zinc concentration in soil mainly through the changes pH as a result of high CO_2 in soil. Guo *et al*. [28] reported that the enhanced plant growth in elevated CO_2 conditions leads plants to compete with microorganisms there in the soil for micronutrient acquisition and this will reduce the available nutrient content in soil. It was concluded that elevated CO_2 decreased the concentration of Zn in wheat crop as a result of the dilution caused by carbohydrate accumulation and high transpiration [29]. In a study done by Wang *et al*. [30] found that CO_2 enrichment and warming enhanced the zinc availability in wheat and they also reported that the availability of micronutrients with the CO_2 enrichment and warming depends on the crop growth stages. Decreased nutrient concentration in different plant parts could activate stress responses in plants were also reported by Barrett *et al*.[31]. In the case of mobilization and acquisition of diffusion limited nutrients, largely P and Zn from decomposing organic matter, mycorrhiza performs significant roles. Elevated CO_2 and the consequent temperature indirectly affect arbuscular mycorrhiza, i.e., in the course of growth responses of plant [32]. Elevated CO_2 found to have very complex results on forest ectomycorrhizal communities with vague effects for health of forest trees [33]. These findings indicating that global warming and elevated CO_2 affect the course of soil nutrients like zinc by some ways through the mycorrhizal action.Manderscheid *et al*. [34] also reported that CO_2 enrichment reduced the concentration of zinc in the stem tissue of wheat. Related findings were reported by Wu *et al*. [35]. Under elevated CO_2 there was considerable reduction of Zn concentration in crops like rice (3.1 per cent), soybean (5.0 per cent), wheat (9.1 per cent), barley (13.6 per cent) and field peas (6.8 percent) was reported by Myers *et al*. [36]. In vegetables there was a decrease of 9.4 per cent zinc in their edible parts reported by Dong *et al*. [37]. A study conducted by Jin *et al*. [38] in different soil types (Vertosols, Calcarosols and Chromosols) and crops (wheat, field pea and canola) fond that irrespective of the soil types as well as crops, elevated CO_2 decreased the grain Zn concentration by 10 per cent. Under conditions of elevated CO_2 and water stress there is a drop in Zn content in wheat [39] and in lentil and faba beans as reported by Parvin *et al*. [40].

Edward and Kamprath [41] reported that reduced or intermediate light intensities increased the severity of Zn shortage in corn. But it is less severe under low light intensity or winter conditions [42]. There were reports that zinc deficiency does not develop so readily in mild sunlight as it does in bright sunlight that means plants are more vulnerable to zinc deficiency in intense sunlight. This correlation is supposed to be associated through auxin activity [43]. It was found that the zinc deficiency lead to the accumulation of more carbohydrates in primary leaves than in roots after exposure to high intensity light [44]. According to Marscher and Cakmak [44] under zinc deficiency, plants are not able to utilize all captivated light energy in photosynthesis that leads to surplus of light energy in leaf cells and thus light-driven generation of highly toxic oxygen free radicals, particularly under high sunshine and long sunny days. Also, plants raised under blue light exhibit zinc deficit symptoms more readily than those grown under red light. Light of high intensity and of short wavelengths inactivates auxin activity.

Boron - Weather interactions

On global scale boron deficiency ranks second next to zinc and is one of the most imperative limitations to crop production [45]. Over the last 60 years about 80 countries reported to have boron deficiency [46]. In general, concentration of total B in soil is reported to be in the range of 20 to 200 mg B kg^{-1} [47], and the availability varies with the soil. Important weather factors in soil distressing the availability of B are moisture, temperature, and organic matter. As mass flow is the major process of B to plant roots, [48], in dry climate areas like arid and semi arid regions, B toxicity results from high levels of B in soils and the B rich irrigation water. As it is mobile in soils, there are chances to filter down in the soil profile with surplus moisture.

Boron uptake is extremely influenced by soil temperature. As the B uptake is linked to the transpiration stream, the temperature effect on B is complex and influenced by the combined effect of soil and aerial temperature on the transpiration rate and so is uniquely different [49] from other elements. Enhance in soil temperature from 25 to 45°C and wetting and drying cycles increased the fixation of boron by kaolinite and montmorillonite clays [50]. Boron adsorption by clay particles reduced with temperature in the range of 10 to 40°C on soils prevailing with crystalline minerals [51]. However, Bingham and Page [52] reported the slight increase in boron adsorption when there is an increase in soil temperature from 10 to 40°C. Later, Fleming [53] found increases boron adsorption with elevated soil temperature. The result of temperature on B adsorption by clays was investigated by many authors [51, 54-57] and found that in a very short reaction time of two hours, as the temperature increases B adsorption found decreased in the pH range of 5.5 – 9.5 [51]. Boron surface assimilation for extended reaction times of twelve hours to sixty days enhanced with increasing temperature [55-57].Thus the initial adsorption of B is exothermic while the subsequent B fixation reaction is endothermic. According to Lovatt [58] lower temperature on root zone increases the B requirement of some plants of tropical / sub tropical origins.

Under drought condition boron availability to plants decreases mainly due to the low mobility of B from soil to roots by mass flow [59-62]. By mass flow and diffusion boron can move fairly long distances to roots. Hence, soil drying decreases B diffusion by reducing the mobility of soil solution and escalating the diffusion path length [63]. Dry weather speeds up the manifestation of boron deficiency symptoms in crops especially in boron deficient soils [53]. This may be as a consequence of plants come across reduced amounts of accessible B when extracting moisture from lower depths at some stage in dry conditions [53]. The link between dry weather and boron unavailability has not been established and some reports found that laboratory drying of the soil increased the fixation of boron. In fields wherever soil is too much dried during the dry year are more prone to notice severe boron deficiencies. Berger [64] suggested the reasons for the manifestation of deficiency symptoms of boron in dry years, compared to wet years, is the most of the plant available of boron is present in the surface, or organic layer of the soil, and as an when this layer becomes dry, plants try to take boron from this layer is limited because of the shortage of water; in this condition plants try to absorb boron from lower horizons, where organic matter and available boron are usually low. Microorganisms in soil without proper tilth and structure, under dry weather will go dormant. As a result the boron supply is cut off. Drought stress/moisture stress in the surface soil accentuates B deficiency in many crops including sunflower, alfalfa, apple and cotton [65-67]. Since the availability of B is more in the surface soil, drying of surface layer will restrict the water and B uptake from this zone and hence drought stress affects the incidence and severity of boron deficiency more than any other micronutrient. According to some studies, the drought induced B deficiency involves moisture stress that restricts the mineralization and plant availability of organically bound B in soil [64, 68, 69].

Boron diffusivity of usually reduced with reduction in water content because dry climate reduces boron mobility and enhances the diffusion path length [63]. However, it was found that repeated extraction of total diffusible boron was not associated with water content [70]. In a study [71] it was concluded that 50 to 100 per cent field capacity conditions boron adsorbed was not vary with moisture differences but another study [72] says that available boron increased with reducing soil water content. Boron fixation was found increased with wetting and drying cycles [50]. The drying effect became advanced with enhancing the amount of B additions [50]. Soil boron is mobile furthermore it can leach fast the crop root zone (rhizosphere) if there’s an ongoing wet spring. Moisture stress in soil reduces transpiration rate, thereby reducing B movement to shoots [58]. Boron toxicity in plants is chiefly affected by B content in soil water and the rate of transpiration. Increasing transpiration as result of high temperature and low relative humidity will accentuate the occurrence of B toxicity in irrigated areas and vice versa [58].

A few studies so far conducted to see the effect of elevated CO_2 on plant micronutrient content reported that CO_2 effect may vary with species, tissues, and even with micro-nutrient itself and there is an inverse association among high CO_2 and micro-nutrient concentrations, also it was clear that seeds are more prone to show a decline in micronutrient concentration than leaves [73-76]. Hagedorn *et al*. [74] found that soil fertility and CO_2 may have interactive effects, specifically, CO_2 enrichment decreased the net accrual of nine (out of 11) studied major and minor nutrients in beech trees (significant for Zn), however in spruce trees it was stimulated 10 of 11 nutrients (significant only for Fe, Zn) on an acidic loam soil. On the other hand, CO_2 enrichment enhanced the nutrient buildup in both species appreciably[74]when studied on nutrient rich calcareous sand. While rising CO_2 concentration may accelerate plant growth initially, some studies suggest that the nutrient content of crops is prone to decline, especially as plants adapt to higher atmospheric CO_2 levels. Increased growth due to elevated carbon dioxide, increased rainfall etc.

created greater demand on soil micronutrient reserves. Mishra *et al*. [77] reported that as the CO_2 increased the leaf boron concentration and boron uptake decreased in geranium plants. The increased grain production under elevated CO_2 increased the availability of B on the whole and other micro and macronutrients on the basis of a given land area reported by Fernando *et al*. [78] and [39].

Generally elevated light intensity increases B deficiency and decreased the severity of B toxicity. Also long day conditions can intensify B deficiency. Oertli [79] reported that total B uptake by barley was stimulated by extended photoperiods and by high light intensities, probably due to increased transpiration. Weather change may also have an influence on the nutritional value of the crop itself.

Manganese - Weather interactions

Manganese (Mn) is an essential micronutrient for plant growth and development. It is needed in chloroplast formation and photosynthesis, nitrogen metabolism, and the synthesis of various enzymes. In, soil Mn exist in three oxidation states: Mn^{+2}, Mn^{+3} and Mn^{+4} among that Mn^{+2} is the main form in which manganese is absorbed by plants. Mass flow and diffusion are the major mechanism by which Mn^{+2} transports to the root surface from soil solution. Manganese availability is influenced by chemical and microbial interactions in the soil [80] as well as by plant factors [81]. Due to its immobile nature in plants deficiency symptoms of Mn are first appears in the young leaves. High amount of soil organic matter (OM) are responsible for the development of Mn deficiency in field crops [82]. Other important factors that are normally related to manganese deficiency are texture, soil moisture, microorganisms, oxidation-reduction potential (redox), and also competing cations.

The major factors which alter the availability of manganese in soil include high organic matter, high pH, sandy texture with low organic matter and over liming. Under dry aerated condition manganese may be less available, but availability may be high under wet soil environments where manganese is in reduced form (Mn^{+2}). However, manganese toxicity can occur in submerged, high-manganese acidic soils. Manganese uptake may decrease with increase in soil pH and at elevated concentration of soil available iron. The incidence and severity of Mn deficiency and toxicity in plant depend on temperature, soil water status and light.

Several environmental variables that are changing as a result of human influences act together with oxidative stress, including increased UV radiation, temperature stress, changing light levels, drought stress, and ozone exposure [83]. These changes are taking place simultaneously with rising Mn bioavailability in forest soils caused by acid deposition and base leaching [84, 85]. Mac Millan and Hamilton [86] reported that increasing the temperature of an organic soil resulted in a pronounced increase in the Mn concentration in carrot leaves. Similarly, Nyborg [87] stated that the occurrence of Mn deficiency in oats was evident on mineral soils only when low soil temperatures were maintained. It was, therefore, postulated that weather conditions, particularly those resulting in soil temperature variations were largely responsible for these observations found in the field studies. Even though chemistry and biochemistry of soil Mn are very complex and poorly understood [80], it is able to predict that soil temperature would change the reaction rates and equilibrium constants of these reactions thus influencing Mn availability. At three- to four-leaf stage, shoot Mn concentration increased with soil temperature from 10 to 20°C in case of wheat and from l0 to 25°C for barley (Table 1). Similar way Mn levels in the plant tissue at the boot stage increased significantly when the soil temperature was increased from 15 to 20°C for the wheat and over the range of l0 to 20°C for the barley. An important feature of this data was the low concentrations of Mn in the barley tissue grown at the l0°C soil temperature [88]. At the same time, manganese concentrations in barley tissue at the three- to four-leaf stage and the boot stage increased significantly with rising soil temperature.

Soil temperature had a very pronounced and interesting effect on manganese uptake by wheat and barley. It is possible that the increase in Mn uptake with increasing temperature was a result of increased plant respiration (root respiration) at the higher soil temperatures. Maas *et al*. [89] showed that Mn uptake was metabolically mediated in 6-day-old barley seedlings. Thus, it could be concluded that the influx of Mn into the plant was temperature dependent and was responsible for the results obtained. The greater Mn values reported at the higher soil temperature may have been due to an increase in the supply (or rate of supply) of soluble Mn in the soil solution. It is probable that at the higher soil temperatures decomposition of the organic soil was greater than at lower temperatures and this may have resulted in a greater release of Mn [89]. According to Ghazali and Cox [90], relative growth rates and Mn accumulation rates of soybeans grown in solution cultures varying both air and soil temperatures and reported a slight decrease in Mn content in leaves with increasing air and soil temperatures. However, increasing the Mn concentrations of the solution resulted in greater leaf Mn tissue contents. This suggests that Mn uptake by plants is dependent on the supply of Mn and other mineral nutrients in the soil solution at higher temperatures. Godo and Reisenaur [91] stated that, plant Mn uptake is controlled by a combination of plant and soil factors; which would both be influenced by temperature. Soil temperatures variation through the growing season between 10-20°C were found to have a profound effect on available Mn as measured by plant uptake and chemical extraction. In a green house study

Sublett *et al*. [92] concluded that in lettuce elevated temperature decreased the Mn concentration.

Under short-term waterlogged environment, available manganese in the Mn^{2+} oxidation state can be reduced to Mn^{+}, which is not accessible to plants. On the other hand, under conditions of prolonged water logging, plant available manganese can be improved [93]. During drying conditions of soil, again manganese availability undergoes modifications. In this situation some of the plant unavailable form of manganese (Mn^{+}) is oxidized to available form (Mn^{2+}), while some available form of manganese (Mn^{2+}) can be oxidized to unavailable form (Mn^{4+}). During the transition stages of soil moisture from flooded to normal there can be a short-term flush of surplus amount of Mn^{2+} leading to temporary manganese toxicity particularly all other conditions are conducive to the incidence of high Mn^{2+}.

Availability of Mn depends on soil moisture due to many ill-defined reasons. One significant factor is the movement of Mn to roots for subsequent uptake. With no assumption as to cause, numerous authors have pointed out that deficiencies tend to be related with less soil moisture levels [82, 94, 95]. On the contrary some researchers have recommended that symptoms arefurther harsh in moist conditions [96]. Moisture variability may account for year to year differences in symptom development. Redox potential is a measure of the concentration of electrons in the soil. This affects the valence of Mn, which in turn affects Mn solubility and availability. The common valences of Mn in soil are Mn^{+2} and Mn^{+4}. The Mn^{+2} form is more mobile in the soil, thus, is more easily transported to roots or leached from the rooting area. Dry soil conditions often reduce the availability of manganese in soil. It was reported that soil moisture was positively correlated with Mn availability in wheat [16]. Because of the pooled effects of low mineralization of organic matter, reduced growth of roots, and low metabolic activity manganese deficiency may be expressed in plants during cold and wet conditions. Under submerged condition excessive concentration of highly soluble form manganese will be formed by the chemical reduction of manganese oxides to soluble manganese (Mn^{2+}).

Effects of rainfall on uptake of nutrient by trees have been established by Barrow *et al*. [97] and Bickelhaupt *et al*. [98] in maples found that higher the precipitation the higher was the foliar Mn concentration. One theory explaining the rise in foliar Mn with high rainfall was that the high soil moisture cause lowering of redox potential and hence more manganese oxide reduction occurs due to the enhanced precipitation. Another hypotheses say that increase in rainfall tended to lower pH in well drained soils via leaching of basic ions and so more manganese was transported to roots via greater mass flow of water in moist, well drained sols [99]. High and low light intensities intensify Mn toxicity and Mn deficiency respectively [82]. Shading reduced the Mn concentration in beans [100]. Horiguchi [101] also reported that shading reduced the concentration of Mn in corn and bean plants. But Mn is found to accumulate in rice under shaded environments than under full day length conditions [102]. Manganese toxicity due to the photo-oxidative stress has significant implications on the effects of global change and ecosystems susceptible to Mn stress [2]. Manganese (Mn) toxicity exists both in natural and agricultural systems [103] highlights the intricacy of the interactions of mineral stress with climate change variables. Mn toxicity was at extreme conditions at high light intensity in common bean (*Phaseolus vulgaris* L) and sugar maple (*Acer saccharum* Marshall). Gonzalez *et al*. [104] reported that surplus manganese can induce antioxidant enzyme systems especially under high intensity light and a genotypes with Mn-tolerance is superior to sustain reduced ascorbate pools than a Mn-sensitive genotype under Mn stress.

Increasing atmospheric CO_2 should reduce transpiration, and hence decrease the uptake of Ca and Mg along with the varying Ca and Mg distribution to growing leaves by altering xylem fluxes. This event may aggravate the inhibition of Mn and leaf metabolism of Ca and Mg. Manganese toxicity due to photo oxidation may be significantly magnified in response to other variables like increasing light intensity. Hence, Mn toxicity along with related photo-oxidative mechanisms may have crucial role in amalgamating changing weather with ecosystem responses [105]. Wang *et al*. [30] found that in wheat CO2 enrichment increased the Mn availability by 35.4 and 32.6% respectively at jointing and ripening stages. Studies conducted by Labanauska *et al*. [106] reported that the high soil CO_2 decreased the levels of N, P, Ca, Mg, and Mn in the tops and the roots but increased the concentrations of Mg and Mn in root. Abbas *et al*. [27] observed that elevated CO_2 supported increased manganese concentration in soil primarily through the changes pH owing to the incidence of high CO_2 in soil. According to Fernando *et al*. [78] and Asif *et al*. [39] the higher grain production under elevated CO_2 increased the total manganese availability and other macro and micronutrients in a given land area basis.

Iron -Weather interactions

Iron is an important constituent of many enzymes linked to nitrogen fixation and reduction, energy transfer, and the formation of lignin. It has a direct role in the production of chlorophyll, and the deficiency may easily be recognized as iron chlorosis in calcareous soil especially in iron sensitive crops. Under field conditions weather factors have a major role in the incidence of Fe deficiency. Also other factors like high soil HCO_3^- in calcareous soils, cold temperature and high moisture content etc can stimulate iron deficiency. The severity of Fe chlorosis is greatly influenced by a combination of high soil moisture and cool temperatures and by hot dry summer [107, 108]. Iron deficiency can be augmented by cool and wet weather particularly in soil with poor available iron. Restricted soil aeration and soil compactness also reduce the iron uptake. Since Fe uptake is controlled by metabolic activity, the uptake and concentration of Fe in plants is influenced by temperature. Brown [109] was reported that change in temperature may either advance or restrain Fe deficiency depending on the crop requirement and availability. Wet and cool season also will enhance the Fe- induced chlorosis as the growth of roots will be reduced under this condition. Also accumulation of CO_2 in wet soil apparently intensifies soil temperature effects. Elevated temperature will increase the Fe chlorosis due to the increased respiration rates and restricted supplies of photo assimilates for energy dependent physiological functions in the roots [110].

Iron deficiency is directly related to soil moisture content since soil moisture affects the plant metabolism, the status of iron and the HCO_3 concentration in the soil solution [109]. Lindsay [111] reported that poorly aerated conditions caused by excess soil water destroy many of the smaller roots and reduce the absorptive capacity of the whole root system. Under hot dry conditions, restricted root growth also leads to Fe deficiency. In acid soils enhanced reduction of soil Fe under waterlogged conditions can result in large quantities of soluble Fe^{2+}. This will lead to Fe toxicity in crops like rice. In a study, Najafi-Ghiri [17] reported that soils with aquic moisture regimes showed the highest values of Fe, while soils with aridic and ustic moisture regimes had the lowest values.

Elevated CO_2 not only enhance the plant growth but also increase the demand for various nutrients. Jin *et al*. [76] reported that continuous rise of atmospheric CO_2 had an effect on iron nourishment in plants (**Table 4**), and ultimately to crop production. However, there is not much information about the relation between Fe nutrition and elevated CO_2 in higher plants [112]. A study conducted by Sasaki *et al*. [113] in marine alga (*Chlorococcum littorale*) grown in Fe-limited condition found that the Fe reductase activity and Fe uptake capacity significantly increased under exceptionally high concentrations of CO_2. Jin *et al*. [76] demonstrated the positive effect of elevated CO_2 in iron nutrition of tomato plants especially under conditions of low iron status by enhancing the iron uptake through the induction of physiological, morphological and molecular changes inside the plant system. In addition they were reported that in certain combination of elevated CO_2 and iron limited conditions are requisite to create iron deficiency symptoms in plants. In a study, Manderscheid *et al*. [34] reported that CO_2 enrichment reduced the concentration of Fe in the wheat tissue. In another study conducted by Wang *et al*. [30] found that under ambient CO_2, warming increased Fe availability by 41.0%, while, under elevated CO_2, warming increased Fe availability by 75.5% in wheat. Elevated CO_2 supported increased iron concentration in soil mainly through the changes pH due to the presence of high CO_2 in soil [27]. The higher grain production under elevated CO_2 increased the overall availability of Fe and other macro and micronutrients in a given land area basis reported by Fernando *et al*. [78] and Asif *et al*. [39]. Under conditions of elevated CO_2 and water stress there is a reduction in Fe concentration in lentil and faba beans as reported by Parvin *et al*. [40]

Table 4 Effect of CO_2 on micronutrient concentration in crop plants studied in past

Plant used for study	Plant part	Nutrient decrease	Nutrient increased	Source
Triticumaestivum L	Seeds	-	Zn	[34]
Triticumaestivum L	Seeds	-	Fe, Mn, Zn	[29]
Solanum lycopersicum L.	Shoot	Fe	-	[76]
	Root	Fe	-	
Hordeum vulgare L	Seeds		Fe, Zn	[34]
Gossypiumhirsutum L.	Seeds	-	Cu, Fe, Zn	[114]
Citrus aurantium L	Leaves	B	Mn	[115]

The effect of light variability on lime induced chlorosis is less compared to soil water and temperature. High weekly evaporation, weekly relative humidity and accumulated rainfall depressed the uptake of iron in green tea shoots [23].

Copper -Weather interactions

Copper is an immobile nutrient required for plant growth and development. Hence, copper deficiency first seen in younger leaves than older leaves. Copper is an essential constituent of several enzyme systems, and also it participate in photosynthesis, cell wall formation, plant metabolism and electron transport. In cereals, older leaves stay green and healthy while the younger leaves turn yellow and wilted, and also the leaf tips show pig tailing. Copper deficient plants usually show a compact look because of the short stems between leaves. Also the flowers appear lighter colour than the normal. Studies on availability of copper under changing weather conditions are very less.

The availability of organically bound Cu is influenced by soil temperature. Mobilization and immobilization reactions are temperature dependent and affect Cu solubility. Mac Millan and Hamilton [86] in a study revealed that in acid soil native and added Cu uptake by carrot under green house conditions was improved when the soil temperature was enhanced by 8 to 20°C. But Sheaffer *et al*. [116] reported that in a field experiment the Cu concentration in corn tissues was not consistently affected by an increase in temperature from 16 to 35°C. In a study Najafi-Ghari [17] concluded that availability of Cu is significantly affected by soil temperature; soils with mesic temperature regime had the maximum values of available Cu, followed by those with thermic and hyperthermic temperature regimes. Li *et al*. [117] found that the increased temperature found to increase the leaf Cu concentration in *Solanum tuberosum*.

Under submergence, copper availability of rice decreased was reported by Beckwith *et al*. [118]. Ponnamperuma [119] reported that complete flooding reduces the water soluble Cu levels probably due to intense reduction and S^{2-} formation in chrysanthemum, which is short day plant and Cu deficiency, delayed the flower initiation. Also under Cu deficient conditions short day plants resembled long day plants [120]. A study conducted by Da Ge *et al*. [24] in maize under different moisture levels found that severe drought decreased the grain Cu concentration by 18 per cent compared to control. Najafi-Ghari [17] reported that soils with aquic and xeric moisture regimes showed significantly higher content of available Cu than those with aridic and ustic moisture regimes. Steffens *et al*. [26] observed that due to flooding the there was a significant decrease in Cu concentration in the shoots of wheat and barley. Wheat genotypes sensitive to water logging found to accumulate less copper in the plant tissues [121].

In a green house experiment, Jiemin Zheng *et al*. [122] studied the effect of elevated CO_2 (700 μL L^{-1}) in *Pteridium revolutum* and *Pteridium acquilinum* plants grown in Cu contaminated soil and found that Cu accumulation was significantly increased under elevated CO_2. There were reports that high weekly evaporation, weekly relative humidity and accumulated rainfall depressed the uptake of copper in green tea shoots [23]. A study conducted by Wang *et al*. [30] concluded that CO_2 enrichment increased the availability of copper in wheat by 59.8%. The more grain production under elevated CO_2 lead to increase the overall availability of Fe and other macro and micronutrients in a given land area basis [78, 39] (**Figure 2**) [123].

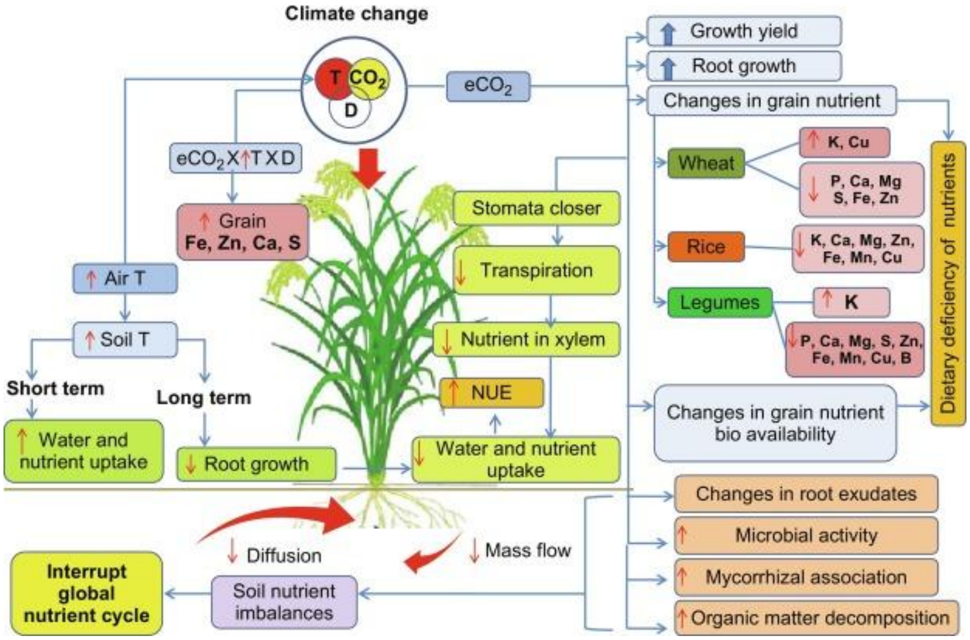

Figure 2 Climate change effect on various essential nutrients [123]

Molybdenum -Weather interactions

Molybdenum, one of the essential micronutrients required in the smallest quantity for plant growth. Molybdenum is vital for enzyme systems which enable the conversion of nitrite to nitrate and nitrate to ammonia. It is also required by bacteria which fix atmospheric nitrogen symbiotically with legumes. Molybdenum deficiency is not very common as its requirement is very much limited. In legumes it is generally expressed as nitrogen deficiency as it helps in symbiotic nitrogen fixation. Since molybdenum is a mobile nutrient, its deficiency symptoms first appears in older and middle leaves than younger. In cauliflower the typical molybdenum-deficiency symptom appears as misshaped leaf blade known as whiptail. Interveinal mottling, marginal necrosis and chlorosis of older leaves are other deficiency symptoms of molybdenum deficiency. Crucifer vegetables are very much susceptible to Mo deficiency.

Molybdenum availability depends mainly on soil pH. As the soil pH decreases the Mo availability also decreases and hence its deficiencies are observed mostly in acid soils of humid regions. Since Mo uptake is metabolically controlled, soil temperature seems to have little effect on the incidence or severity of Mo deficiency. In acid soils high temperature accentuates the fixation of MoO_4 [124]. Low temperature reduces the N fixation in legumes and thereby decreases the Mo requirement of legumes as the Mois directly related to the N fixation.

Sublett *et al*. [92] reported that elevated temperature in lettuce decreased the concentration of Mo. In acid soil submergence increases the soluble fraction of Mo due to the reduced fixation of MoO4 under higher pH due to submergence [119]. In acid soils under wet conditions, Mn concentration was found to be increased in alsike clover [125] and alfalfa [126]. Gupta and Sutcliffe [71] reported that Mo availability to plants was reduced under drier soil conditions. Since Mo is required for N fixation in legumes the factors which affect N fixation like quantity and quality of light and photoperiodic duration affect Mo requirement of crops especially legumes. Molybdenum availability depends on soil moisture especially in poorly drained organic soils [125]. Plant grown in poorly drained soils showed high amount of internal molybdenum concentration [127]. Significant loss of applied molybdenum was reported in well-drained sandy [128].

Chlorine -Weather Interactions

Chlorine is also one of the essential element needed for plant growth and development but the quantity required is very much low similar to other trace elements. In several parts of the world, soil is deficient of chlorine and plants are responding to the added doses of this element by ways of better growth and yield. Transpiration and stomatal regulations are the main functions of chloride in higher plants. The critical limit of chloride in plant is reported as 15 mg kg-1 and lowers than this concentration, plants used to show response to added chlorine. But crops like cereals may respond upto 30 mg kg^{-1} of chloride. Wilting is a general deficiency symptom of chlorine and since transpiration is also affected the plant is often chlorotic in appearance. Soils with crop cover can have chloride build up as the soil is not drained properly. In such soils natural regulation by leaching of Cl^- may not happen. Under conditions arid and semi arid climate with low rainfall there is more chances of deposition of salt in high concentration. In addition, usage of irrigation water contaminated with high concentration of chlorine often lead to toxicity of chlorine. Toxicity of chloride results in burning of margins and leaf tips, premature yellowing, bronzing, and premature leaf falling. Scorching of stem and roots are the major symptoms in tuber crops as well as seedlings. Chloride toxicity occurs mainly through the osmotic effects. Physiological effects like decreased carbon dioxide absorption and lower protein production may be occurred due to chloride toxicity. In coastal areas leaf scorching occurs mainly due to the continuous saline drift and sea water sprays. Since the element is related to build up osmotic pressure in plants, the toxicity or deficiency also differs through the moisture content and moisture holding capacity of the soil. Due to the mobile nature of chlorine inside the plant system most of its physiological functions are related to salt effect like stomatal opening and balancing the electrical charge.

Chlorine has been regarded as an element often accumulating in detrimental quantities-particularly in semiarid regions so its removal to the seas along with other excess salts constituted a problem. On the other hand, there might be areas where adequate natural supply of chlorine is limited and hence chlorine addition through fertilizer materials is benefited to crops. Mahonachi *et al*. [129] found an increase of Cl^- concentration in leaves and roots of papaya subsequent to 34 days of moisture stress. Hence, along with organic solutes these ions contribute to osmotic regulation in plants and therefore, under conditions of low supply, symptoms are visible mainly in aerial meristems, young leaves and reproductive organs.

Chlorine is a highly mobile element in soil and hence chances to leach away under high rainfall conditions becomes a matter of concern as far as the weather change is considered. Plants used to get a measurable amount of chlorine through rain water. In high rainfall coastal areas this amount may be much higher. Elevated soil temperature can cause the depletion of soil moisture and hence the accumulation of salt in soil. Low rainfall will lead to low soil moisture and less leaching of salts. The weather change hence will lead to build more areas with salt problems. Chloride (Cl^-) is readily leachable, and hence high precipitation during the autumn and winter often lead to deficiency of chlorine [130]. Irrigation water can also act as a source of chlorine. Hence there will be chances of more chlorine toxicity in the soil through irrigation water. The high rate of transpiration due to high atmospheric temperature also will cause the accumulation of more chlorine in the above ground parts of the plants producing chlorine toxicity symptoms in plants.

Conclusion

Plant nutrition is affected by the varying climatic factors directly and indirectly through weather change. Various studies revealed that the availability of major and micronutrients were increased/decreased due to the fluctuations in weather factors. These fluctuations may create both deficiency as well as toxicity of micronutrients as the barrier is very narrow. The quality of food is also governed by micronutrient availability to plants. Hence the study of micronutrient availability in soil and plant is very much essential to improve the food production and quality in the changing climatic scenario.

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