NUTRIENTS AND WATERLOGGING

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INTRODUCTION

Waterlogging can drastically increase or decrease the availability of soil nutrients. Short-term waterlogging (1-7 days) reduces the capacity of the roots of most crops to absorb nutrients from the soil, whereas chronic waterlogging can severely damage roots and increase absorption of soil elements, sometimes to toxic levels. Waterlogging alters soil pH, which in turn affects nutrient availability. Changes in the availability of one nutrient may alter that of several others. Nutrition studies of waterlogged crops need to be interpreted with caution.

Having outlined the complexity of this topic, I now intend to summarise the soil and plant mineral relations during waterlogging, followed by a brief review of the scientific principles to improve understanding of the problem and to point to methods of dealing with it. Key references are listed to enable those who wish to delve further into the scientific literature.

SUMMARY

Severe waterlogging destroys nitrate, favours ammonification of N_2 to NH_4, increases soil availability of P, Si, Fe and Mn, decreases availability of S, Zn and Cu, and generates toxic substances that interfere with nutrient uptake. Flooding converges the pH of acid and alkaline soils to about 7, which favours nutrient absorption by waterlogging-tolerant plants, an increase in the availabilty of P, and mineralization of organic matter, regardless of the soil pH before flooding. The high concentrations of cations and bicarbonate ions produced by soil metabolism in

flooded soil displace ions from soil colloids into the soil solution. Thus K, Ca, Mg and P levels increase and can benefit waterlogging-tolerant plants. Leaching of these nutrients may impoverish sandy soils.

Flooding depresses the concentrations of N, P, and K in shoots, generally decreases N concentrations in leaves, and almost always decreases total N uptake. Waterlogging reduces shoot N of legumes by reducing N fixation and nodulation of roots by N-fixing bacteria. P uptake is often a balance between the increased availability of P on flooding and less uptake due to lack of O_2. Flooding inhibits the accumulation of Ca and Mg less than it inhibits N, P, and K. Sodium levels generally increase under waterlogging. The availability of Fe and Mn increases with flooding, but total plant levels often decline because of inhibited root uptake or severely inhibited growth due to phytotoxic effects. Tissue concentrations and total contents of Zn generally decline under waterlogging, whereas concentrations of Cu and B may remain constant, decrease, or increase.

SOIL CHEMICAL RESPONSES TO WATERLOGGING

Oxygen In non-waterlogged soil, normal aerobic respiration transfers electrons to O_2, thereby releasing energy. Waterlogging virtually cuts off the O_2 supply to the soil and prevents aerobic respiration. Anaerobic respiration and fermentation may proceed, but release only about 5% of the energy released by aerobic respiration.

Carbon Carbon is the basic element of organic matter. Organic matter disappears rapidly in warm, moist, aerated soil because the abundant energy released by the aerobic respiration of soil microbes rapidly generates even more microbial activity. In waterlogged soil, anaerobic bacteria function slowly at the low energy level of fermentation, thus organic matter decomposes slowly and may accumulate, as often occurs in marshes and waterlogged depressions. The main end-products of fermentation are CO_2, CH_4 and humus. Most of the CO_2 produced in waterlogged soil dissolves, escapes or forms a solid; some accumulates as gas, but rarely to toxic levels.

Nitrogen Lack of O_2 in waterlogged soil stops the conversion of organic N to inorganic forms (*mineralization*) at the NH_4^+ (*ammonification*) stage. NH_4^+ often accumulates, as *immobilization* (assimilation by microbes) of N is slow in waterlogged soil. High concentrations of organic matter, high temperatures and alternate drying and flooding increase ammonium production, which may exceed 300 ppm of soil within two weeks after submergence. Dry soils may contain up to 350 ppm of NO_3^-, but within a few days of submergence most of this is lost as N_2O and N_2 by *denitrification*. Decreasing the O_2 content of the soil air from 20 to 5% in cores of a clay loam increased denitrification losses from 2.3 to 9.4 kg N ha^{-1} each day. Chemical and biological *fixation* in soil renders N temporarily unavailable to plants. Ammonium can be chemically fixed in the clay lattices when NH_4 concentration is high, when soil is alternately wetted and dried and when soil pH is high. NH_4 may also condense with phenolic substances to form humus. Biological fixation of N by microbes is slower in anaerobic than in aerobic soil. Materials with variable C:N ratios such as straw can immobilize N, whereas leguminous green manures readily release N within 2-3 weeks. High concentration of NH_4^+, high pH and high temperature favour *volatilization*. Up to 30 kg N ha^{-1} of urea added to border check irrigation water on cracking clays may be denitrified within 20 h of flooding. Unfertilized fields can also lose N by volatilization and denitrification.

Manganese, Iron and Sulphur Within 1-3 weeks of flooding, almost all active soil Mn(IV) is reduced chemically and biologically to Mn(II) compounds that are more soluble than those of Mn(IV). The reduction of Mn(IV) precedes that of Fe(III). Soils with low pH, high Mn(IV), high organic matter and high temperature build up water-soluble Mn(II) as high as 90 ppm within 1-2 weeks of flooding. The Mn(II) thereafter declines to a stable level of about 10 ppm due to precipitation to $MnCO_3$. Alkaline soils low in Mn contain up to 10 ppm Mn(II).

From 5-50% of active Fe(III) in soil may be reduced within a few weeks of flooding, depending on temperature, organic matter content, and NO_3^- concentration. Fe(II) may tie up O_2 diffusing into the soil. Acid soils that are high in organic matter and Fe(III) build up concentrations as high as 600 ppm within 1-3 weeks of flooding, and then decrease to stable levels of about 50-100 ppm. In neutral and calcareous soils low in organic matter, the concentration of water-soluble Fe(II) may be $<$ 1 ppm, due mainly to relatively more Fe being in the precipitated oxidised form than in acid soil.

Anaerobic bacteria use fermentation products and H_2 to reduce sulphate mainly to H_2S. Strong acidity, NO_3^- and low temperature retard sulphate reduction. SO_4^{2-} initially desorbs from clay surfaces especially at high pH, and is then reduced mainly to H_2S, which in turn may precipitate with heavy metals (Fe, Zn). This keeps H_2S levels below 0.1 ppm, the toxic limit for rice.

Phosphorus In flooded acid soils, Fe(III) and Al phosphates release phosphate as pH increases, while in flooded alkaline soils, Ca phosphates liberate phosphate as the pH decreases. Phosphate ions released may be resorbed by clay and hydrous oxides of Al and Fe, or they may diffuse to oxidized zones and be reprecipitated.

MINERAL RELATIONS OF SHOOTS DURING WATERLOGGING

Jackson and Drew (1984) reviewed numerous studies and showed that: (i) flooding depresses the concentrations of N, P, and K in the shoots; (ii) ion accumulation is inhibited to a greater extent than photosynthesis and dry matter production; and (iii) anaerobic conditions almost immediately inhibit nutrient uptake and radial transport by roots of nonwetland species. The effects of waterlogging on shoot concentration and uptake of 13 elements are summarized in Table 1. These showed that shoot concentrations of nutrients are usually decreased, but are often increased or unaffected. However, total shoot uptake of most nutrients is generally reduced by waterlogging, since growth is usually reduced. Table 2 confirms this for cotton at Narrabri.

Flooding generally decreases N concentrations in leaves, and almost always decreases total N uptake. The initial soil N status and denitrification affect uptake responses to flooding. Inhibition of N and K uptake rather than unavailability is primarily responsible for early deficiency symptoms in wheat. However, P uptake is often a balance between the increased availability of P on flooding and the inhibition of uptake due to lack of O_2. Flooding appears to have a much less inhibitory effect on accumulation of Ca and Mg than on N, P, and K. Sodium, which appears to be actively extruded by aerobic roots, generally increases under waterlogging, possibly because extrusion becomes less efficient.

Waterlogging reduces shoot N of peas and other legumes by reducing nodulation of roots by N-fixing bacteria, and by suppressing the activity of the enzyme nitrogenase, which is involved in reducing N_2 to NH_4^+. Vesicular-arbuscular mycorrhizae, which may improve plant uptake of phosphate and possibly other soil-immobile nutrients, fail to develop on most crop plants in wetland habitats.

The availability of Fe and Mn increases with flooding, but total plant levels often decline because of inhibited root uptake or severely inhibited growth due to phytotoxic effects. Dissolved CO_2 increases P in solution, which in turn precipitates Fe and reduces Fe uptake, causing chlorosis. Foliar sprays of $FeSO_4$ prevented chlorosis in flooded wheat. Tissue concentrations and total contents of Zn generally decline under waterlogging, whereas concentrations of Cu and B may remain constant, decrease, or increase.

The provision of fertilizer can partially offset the anoxia-induced inhibition of transport to the shoot, and may thus ameliorate the effect of waterlogging. Reduced uptake of inorganic nutrients caused most of the waterlogging damage of barley shoots. Work on barley confirmed that nitrate fertilizer corrected a nutrient deficiency rather than provided an alternative electron acceptor for anaerobic respiration. N fertilizer prevented waterlogging damage of wheat and barley when applied daily to the soil surface, provided that the surface 50-100 mm of soil was not waterlogged, and foliar application of urea to flooded wheat delayed senescence. Hodgson and MacLeod

(1987, 1988) confirmed that a temporary deficiency of N following furrow irrigation accounted for most of the yield loss due to waterlogging of cotton, and that foliar applications before irrigation can recover yields under certain conditions. Recovery was best under low to optimum soil N fertility levels, when waterlogging was low to moderate but not severe, and when conditions were hot and sunny.

CONCLUSIONS

Waterlogging affects plant nutrients by changing either soil availability or root absorption. Both effects are complex and it is their interaction which is responsible for the growth and yield responses that we observe. Soil reactions under waterlogging are dominated by the need of soil microbes to continue to respire in an environment that is oxygen deficient. Oxygen is needed to accept electrons during respiration, so that the substance losing the electrons can release energy. As oxygen is depleted in waterlogged soil, microbial respiration uses alternative substances to accept electrons and these in turn become chemically altered. There is a well-defined sequence in which different soil constituents are affected in this way: first oxygen is reduced to oxides or water, then nitrate is reduced to nitrite, nitrite to nitrous oxide, manganic to manganous ions, ferric to ferrous ions, sulphate ions to hydrogen sulphide, carbon dioxide to bicarbonate, and nitrogen to ammonium ions. The sequence of changes can be accurately predicted from thermodynamic principles, but the rate and relative importance of chemical changes are less predictable because they relate to the severity and duration of waterlogging, soil physical and chemical properties and climatic conditions. In addition, several factors may act coincidently, and so delineation of separate effects is difficult, particularly under field conditions. Not all factors are important in every waterlogged soil, but an awareness of the limitations which chemical effects can impose and careful definition of the important soil factors will assist with interpretation of results and comparison between fields and between seasons.

FURTHER READING

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Table 1. Survey showing the number of studies reporting the concentration and uptake of mineral elements in plant shoots to be less, the same, or more after waterlogging.

Element	Concentration (ppm)			Uptake (kg/ha)		
	Less	Same	More	Less	Same	More
N	18	2	5	11	0	0
P	13	6	5	7	0	2
K	25	4	2	10	0	0
Ca	12	8	3	8	1	0
Mg	14	3	3	10	0	0
Cl	0	2	1	3	0	1
Na	2	4	10	3	3	1
Fe	3	5	9	6	1	1
Mn	5	8	6	6	2	0
Cu	4	6	2	6	2	0
Zn	6	4	2	6	1	0
Mo	0	0	1	3	0	1
B	3	1	3	5	0	0

Table 2. Effect of duration of furrow irrigation (waterlogging) on the concentration and uptake of mineral elements of cotton shoots at Narrabri on 22 January, 1987.

Element	Duration of irrigation (h)	Concentration (ppm)	Uptake (kg/ha)
N	4	22467	66.1
	32	21267	58.2
P	4	3438	10.0
	32	3314	8.3
K	4	19947	60.2
	32	20737	52.8
Ca	4	22608	67.5
	32	21330	52.7
S	4	6808	18.7
	32	5838	14.6
Mg	4	5838	16.9
	32	5555	13.7
Na	4	1664	4.79
	32	1881	4.46
Fe	4	321	0.99
	32	313	0.91
Mn	4	70	0.20
	32	67	0.17
Zn	4	159	0.46
	32	156	0.33
Cu	4	22	0.07
	32	30	0.08