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The Interactions between the Supplies of Water and Nutrients Available to Crops: Implications for Practical Progress and for Scientific Work

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The interactions between the supplies of water and of nutrients available to crops: implications for practical progress and for scientific work

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Many experiments have shown that the interactions between the supplies of water and of plant nutrients have large effects on crop production and on the efficiencies of both irrigation and fertilizers. Biological constraints, such as pests and diseases, also affect the returns from these inputs. High efficiency in the use of water is only achieved when crops have access to adequate supplies of nutrients. Similarly, full returns from fertilizers are obtained only when water supplies are sufficient for the needs of the crop; but water applied in excess or at inappropriate times may cause large losses of mobile nutrients, particularly of nitrogen, from the system.

Water status regulates the processes of mass flow and diffusion of solutes in soils, which determine nutrient uptake. Water-use efficiency depends on physiological processes in plants and these are affected by nutrients. Nitrogen is often responsible for rapid increases in leaf area so that photosynthesis is increased and evaporation of water from the soil surface is reduced. Potassium ions have a vital role in osmotic processes in the plant, and particularly in stomatal regulation. The effects of drought are often associated with reduced phosphate uptake. Water supplies also regulate the microbiological processes involved in soil fertility, and particularly the biological fixation of nitrogen.

Experiments have shown that the method and timing of irrigation affects the efficiency of fertilizers. Therefore the practical management of crop nutrition and irrigation should be carefully coordinated to secure the maximum return from both inputs to the system. Drip (trickle) irrigation systems make it possible to apply both inputs in one operation to the roots of the crop (‘fertigation’) so that maximum fertilizer efficiency is achieved. There is a case for further investigations on subsurface irrigation for appropriate crops and conditions.

In the further research that is required to achieve high efficiency in irrigated production systems the emphasis must be on multidisciplinary field experimentation, testing water, fertilizers, and other inputs needed in the system. The experiments will also form a basis for the work needed in both plant physiology and soil science. This research should lead to the development of models of the production systems, which will be used as a basis for the improved recommendations to farmers on the use of water and of fertilizers which are needed to improve food production.

1. INTRODUCTION

1.1. *Constraints to the growth of plants*

In natural conditions the growth of plants is limited by physical, chemical, and biological constraints. When two or more constraints operate at one time they interact so that their combined effect in depressing growth is greater than the sum of their individual effects. When developed farming systems are established the constraints are overcome by inputs. These inputs in turn interact to raise yields so that when no constraint remains the farmer harvests the potential yield set by the genetic capacity of the plant, the photosynthetically active radiation that is received, and the carbon dioxide content of the air. Penman (1971) expressed this relation in these words: 'For a given farming system there is a limit to the yield attainable when water supply is adequate, and it is the task of the remainder of agricultural research to raise this limit. Water cannot do so, but shortage of water can prevent a crop yield from reaching its optimum.'

1.2. *The water–nutrient interaction*

Constraints caused by water shortage are overcome by irrigation and nutritional constraints by applying fertilizers. These two inputs generally interact so that their combined effect is greater than the sum of their individual effects as measured when each is tested alone. Other factors, of chemical, physical, or biological nature, may complicate all investigations of the water–nutrient interaction. When there is any reason to suspect that any pest or disease may attack the crop, appropriate inputs must be tested to examine the three-factor interaction; the intention will be to develop a system that avoids the third constraint and secures the maximum benefit from additions of water and of nutrients.

There is a worldwide need for more information on the water–nutrient interaction. Wherever irrigation is introduced, increases in the use of fertilizers are likely to be justified. Their use can only be scientifically planned by a knowledge of the interaction as it applies to the crop and to the region. Similarly, decisions on whether the introduction of fertilizers into an area will be economically justified will often depend on information on the water status of the soils, on the possibilities of irrigating if this is required, and on the separate and combined effects of the two inputs.

2. Processes in soils and plants which affect nutrient uptake and efficiency

2.1. *Processes in soils*

Mass flow of water in soil takes to the roots the ions that are dissolved in the soil solution; this mechanism is very important for transporting the nitrate that crops take up. A study of soils in the U.S.A. by Barber (1964) showed that maize obtains more calcium and magnesium by mass flow to the root surface than the crop needs, but that less than 10% of the potassium and less than 1% of the phosphorus needed is transported to the root by this mechanism. Almost all of the P, and most of the K, that annual crops take up has to diffuse through the soil moisture to the spaces in soil that roots occupy. Potassium and phosphate ions both interact with soil surfaces and therefore move much more slowly in soil moisture than in a simple solution. Although potassium ions move more quickly than phosphate ions do, they are much less mobile than chloride or sulphate ions.

The uptake of nutrients may be affected by decreasing soil moisture before transpiration by the crop is reduced. Adequate water supplies will dissolve nutrients and promote maximum transpiration and therefore uptake by roots of the mobile nutrients which are transported by mass flow. Diffusion of the less mobile nutrients will be promoted where there are continuous films of water and water-filled pores which connect roots and nutrient reserves in soil. When topsoils are dry, subsoils may supply adequate water, but then if nutrients are adequate in the topsoil but are inadequate in the subsoil, irrigation will be beneficial by promoting uptake of nutrients in the topsoil.

Most work on the transport of nutrients has been done with the five major nutrients N, P, K, Ca, and Mg; there is little information on the interaction between the sulphur nutrition of crops and their water supply. Similarly there is very little practical information from field work on interactions between most of the micronutrients and the water available to crops. Boron deficiency is said to be accentuated by drought, but when large amounts of water are applied borate may be lost by leaching. There is an urgent need to extend investigations on the water–nutrient interaction to include studies of sulphur and micronutrients.

2.2. *Physiological processes in plants*

Nutrients have specific effects within plants. Nitrogen quickly increases leaf area and consequently lessens the radiation that reaches the soil, thereby diminishing evaporation of water from the soil surface. Several nutrients promote root growth so that better use is made of water reserves in soils. While drought-stressed plants may contain more than normal concentrations of nitrogen, the uptake of phosphorus may be so restricted by dry soil conditions that its deficiency becomes a major factor in the effects of drought on plant growth. Adequate supplies of potassium are essential for the efficient regulation of osmotic and stomatal processes. The concentrations of K^+ in plants are increased by irrigation, the effects of drought on K uptake are greater than the effects on dry matter production. When turgor pressure is maintained by a good potassium status all metabolic processes proceed unimpeded. In particular a sufficient turgor pressure is essential to ensure continuous cell elongation. Potassium has an important role in regulating the activity of the stomata. If stomatal regulation is optimal the plants use their water most economically while taking in sufficient CO_2 to optimize the ratio of water used : dry matter produced.

3. Experimental work on the interaction between nutrients and water

The nature of this very important interaction is certainly complex; efforts to elucidate it require experiments on crops, preferably grown in the field, and associated work on crop physiology and soil properties. Only when we understand clearly the processes involved will it be possible to use the information to plan irrigation and fertilization so that the maximum efficiency of both inputs is achieved. These processes include biological factors which affect the returns from both water and fertilizers.

3.1. *Cotton in the Sudan*

One of the earliest multifactorial experiments relevant to this dicussion, made by Crowther (1934) in 1928–1929, tested the effects of all combinations of three rates of N application (as ammonium sulphate) and three rates of irrigation on growth and yield of cotton. Table 1 shows that there were profound interactions between water and nitrogen applications. The recovery of N by seed cotton was doubled by the high rate of water. Crowther pointed out that 'the type of interaction between the factors was such that the increase in response to either factor increased with a higher level of the other factor.... In no sense does the Liebig's law of limiting factors hold.' The shapes of the yield curves indicated that 'the experimental treatments were much below maximal and that further increases in both water and nitrogen would have increased the yields considerably'.

TABLE 1. THE EFFECTS OF THREE RATES OF NITROGEN FERTILIZER AND OF WATER ON THE YIELD OF SEED COTTON AND THE PERCENTAGE OF NITROGEN RECOVERED BY THE CROP

(from Crowther 1934)

nitrogen fertilizer applied/(kg N ha^{-1})	rate of irrigation water/(m^3 ha^{-1}) 535	890	1250
	yield of seed cotton as percentage of control		
0	100	112	115
67	141	177	203
134	165	220	281
	percentage of applied N recovered by the crop		
67	18	26	38
134	17	21	35

Gregory *et al.* (1932) extended this work on cotton by including two cultural factors (sowing dates and plant spacings) in experiments testing irrigation and N fertilizer. The best yields were given by sowing on 11 August combined with close spacing, heaviest irrigation, and N fertilizer. First-order interactions (treatments in pairs) were all significant except for spacing–water rate. Of the second-order interactions (each involving three factors), sowing date–water–N, and sowing date–spacing–N, were significant. This latter effect apparently arose from the need to establish a full root system to take up the N before it ceased to be available; close spacing therefore greatly increased the efficiency of N fertilizer. No third-order interaction (involving all four factors) was significant. The interaction of sowing date with other factors was associated with the incidence of Blackarm disease (caused by *B. malvacearum*) which was spread by the late rains; early sowing diminished the risks from the disease. This pointed to the need to include a fifth factor – disease control – in such experiments.

3.2. *Spring wheat in England*

Widdowson & Penny (1965) grew spring wheat at Woburn on loamy sand soil that was poor in N and had a small water-holding capacity. Shortages of water and of N, and the presence of take-all disease (caused by *Gaeumannomyces graminis*) and of the cereal cyst nematode (*Heterodera avenae*), had all been identified as major constraints. The whole area received 75 kg N ha^{-1} and then increasing rates of N were tested in factorial combinations with irrigation and with formaldehyde to control soil-borne pests and diseases. The results, summarized in figure 1, showed how the inputs raised yields and how they interacted. The efficiency of the N fertilizer was greatly increased by irrigation, and there were further gains from the input to control pests and diseases of the roots; the middle rate of N tested then produced the largest yield. The highest yields recorded were four times larger than those on the 'control' plot – and these latter would have represented a farmer's yield on such land where 75 kg N ha^{-1} was normally recommended in the 1960s and where irrigation is rarely used for cereals, and soil fumigants are not used at all.

Such information on the identification of several constraints and their interactions, and on the way that inputs build up yields, would be invaluable in all parts of the world where attention is being given to the improvement of crops grown on soils and in climates where constraints reduce yields seriously.

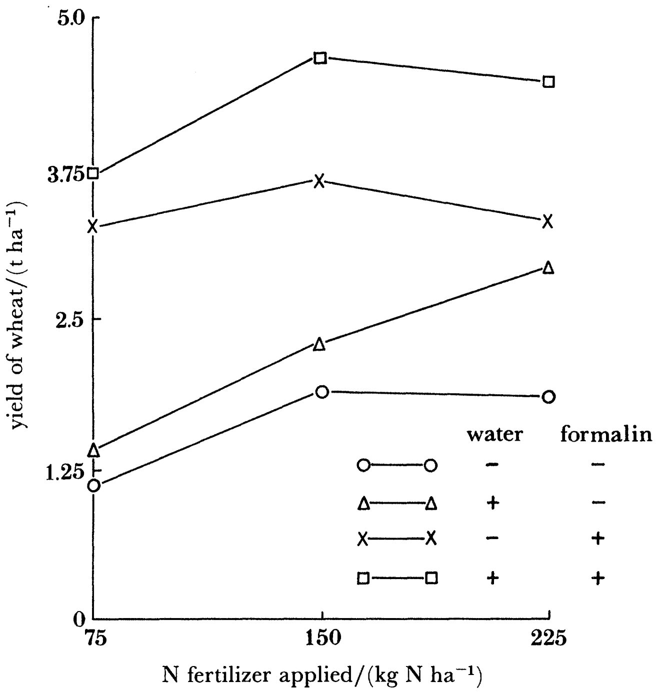

FIGURE 1. The effects of supplying extra water, and of partly sterilizing soil with formalin, on the response of spring wheat to nitrogen fertilizer at Woburn Experimental Station. From Widdowson & Penny (1965).

3.3. *Grass–clover herbage in England*

Experiments at Rothamsted and Woburn described by McEwen & Johnston (1984) grew a mixture of perennial ryegrass with a new long-petiole variety of white clover (Blanca). Nitrogen fertilizer and irrigation (applied when the soil-moisture deficit reached 25 mm) were tested together with pest-control treatments consisting of aldicarb applied in spring, benomyl plus phorate applied after each cut, and a benomyl spray applied in winter. Yields obtained in 1980, given in table 2, show that both lack of water, and pests and diseases, constrained production of the herbage at both sites; there were very large interactions between irrigation and pest control which raised yields to over 13 t ha^{-1} of dry matter without the use of N fertilizer. When N was applied, the gain at Rothamsted (2.9 t ha^{-1}) was more than doubled by applying extra water and pest control. At Woburn, N fertilizer alone had little effect on the yield of herbage but this yield was nearly doubled by applying water together with pest control. Although the pesticides had large effects on yields at Woburn without irrigation, the increases in yield from extra water were small unless the pests were also controlled.

These experiments were done on very different soils, clay loam at Rothamsted and loamy sand at Woburn; nevertheless productivity at the two sites was nearly identical when the constraints caused by water shortage and by pests were controlled, both when the clover provided the N and also when N fertilizer was applied. The removal of constraints increased the amount of nitrogen that was biologically fixed and harvested, corresponding to the increases in yields; this effect is discussed later, see §6.1.

TABLE 2. YIELDS OF LEYS OF PERENNIAL RYEGRASS WITH BLANCA WHITE CLOVER AND THE AMOUNTS OF NITROGEN IN THE HARVESTED HERBAGE AS AFFECTED BY IRRIGATION, PATHOGEN CONTROL, AND NITROGEN FERTILIZER, IN FIELD EXPERIMENTS AT ROTHAMSTED AND WOBURN EXPERIMENTAL STATIONS

(from McEwen & Johnston 1984)

nitrogen fertilizer applied/ ($\mathrm{kg\,N\,ha^{-1}}$)	pathogen control	Rothamsted		Woburn	
		without irrigation	with irrigation	without irrigation	with irrigation
		yields of dry matter harvested in 1980/($\mathrm{t\,ha^{-1}}$)			
0	without	9.0	9.6	7.4	8.6
0	with	9.9	13.1	10.2	13.2
400	without	11.9	10.9	8.1	8.5
400	with	14.5	15.4	12.7	15.1
		total amount of N in herbage, average 1978–1981/($\mathrm{kg\,N\,ha^{-1}}$)			
0	without	252	259	225	294
0	with	298	350	280	377

3.4. *Maize in Israel*

Shimshi (1969) stated that a maize experiment he described indicated that the interaction was of the limiting-factor type. At the highest level of N applied, yield was entirely governed by water supply; with the highest level of water supply the amount of nitrogen became the limiting factor. Shimshi commented that with this type of limiting-factor interaction, when one factor is at a low level which limits growth to the exclusion of the other factor, the mutual replaceability of factors is inefficient; the yield of the moisture-stressed crop cannot be raised by giving more N fertilizer. At intermediate levels both factors may be mutually replaceable; decisions on the levels of factors to be used in practice then rest on the economic aspects of the responses obtained and the costs of the inputs.

3.5. *Wheat in Israel*

Shimshi & Kafkafi (1978) investigated the interaction between supplemental irrigation and N fertilizer applied to autumn-sown wheat in the Negev region of Israel. Early (28 November) and late (12 March) irrigation (each supplying a total of 275 mm of water), were tested on the crop, which had been sown on 17 November and had received 363 mm of rain. Four rates of nitrogen (from 0–240 kg N ha^{-1}) application to the seedbed were tested. The large interaction of irrigation with N was mainly associated with late irrigation. When only early irrigation was applied, the optimum dressing of N was 120 kg N ha^{-1}; with the late treatment 180 kg N ha^{-1} was needed for the maximum yield, which was similar to that produced by early irrigation; a combination of early and late irrigation produced slightly larger yields than were obtained with late irrigation alone. Shimshi & Kafkafi (1978) also examined the mechanism of the interaction between irrigation and nitrogen by examining their effects on the yield components of the crop. Irrigation prevented the adverse effect of nitrogen applications on the number of kernels per ear, and the mass of each kernel. Late irrigation was too late to affect the number of kernels, but it prevented any damage by drought to the mass of individual kernels. Excess nitrogen had an adverse effect on the development of water stress through its effects on water depletion and on stomatal openings.

4. The effects of fertilizers on the efficiency of water

The interaction between nutrients and water results in a larger yield being grown per unit of water available in soil or applied as irrigation. When fertilizers increase growth the larger crop may not require more water, or it may need a little more; but any extra requirement will certainly not be as large as the proportional increase in yield. Water-use efficiency (w.u.e.) is measured by the ratio:

$$\frac{\text{yield of crop (total biomass or saleable product)/(kg ha}^{-1}\text{)}}{\text{water used by the crop/mm}}.$$

The effects of fertilizers and soil fertility status on w.u.e. have been discussed by several authors, notably by Viets (1962) and Viets *et al.* (1967).

4.1. *Very early work in England*

Over 130 years ago John Bennet Lawes (1850) investigated the transpiration of crops in relation to their nutrition. He recognized the need to distinguish between transpiration from the plants and evaporation from the soil and he prevented the latter from occurring in the experiments he made in pots which were protected from rain. The soils used were from a cereal experiment which provided these contrasts: (i) without fertilizer; (ii) with salts of K, Mg and Na plus superphosphate (designated 'minerals'); (iii) 'minerals' plus ammonium chloride. A few of his results are shown in table 3, in the units that he used. The production of dry matter was greater, per unit of water used, with fertilized than with unfertilized soil. Lawes emphasized, in 1850, that an understanding of the effects of nutrition on water use required physiological as well as chemical work. Many years were to pass before the subject was further investigated in Britain.

TABLE 3. COMPARISONS OF THE AMOUNTS OF PLANT MATERIAL PRODUCED BY UNIT WATER TRANSPIRED BY CROPS GROWN IN FERTILIZED AND UNFERTILIZED SOIL

(from Lawes 1850)

	soil used		
	unfertilized	minerals only	minerals + N
crop	number of grains[a] of dry matter fixed by the plants for 100000 grains[a] of water given off		
wheat	404.2	449.7	485.6
peas	385.9	474.4	—
clover	371.5	437.0	677.3

[a] 1000 grains = 64.8 g.

4.2. *Recent work in England*

H. L. Penman initiated experiments on loamy sand soil at Woburn Experimental Station in 1951. The effects of combinations of irrigation water and fertilizer were tested on a wide range of farm crops. Penman (1971) summarized the results of his early experiments by using the model:

$$Y = kE_{\mathrm{T}},$$

where Y = total yield of crop, E_{T} = evapotranspiration when water is not limiting growth, and (in Penman's words) 'k represents the maximum possible response to irrigation'. Where irrigation was applied in the experiments the soil-water content was returned to field capacity so, in his discussion, Penman was considering crops where irrigation avoided all loss of plant growth by moisture stress, total growth then being proportional to total active transpiration. The values of k varied from crop to crop and with the amount of N fertilizer applied. Thus in one experiment on cocksfoot grass (*Dactylis glomerata*) where 19 kg N ha^{-1} was applied per cut, the value of k was 0.20 t ha^{-1} cm^{-1}; with twice as much N per cut, k was 0.27. The values of k measured in terms of dry matter yields were stated for a number of crops. Sugar beet was exceptional in having $k = 1.0$; Penman (1971) commented that for other crops the values were similar, with a general average near $k = 0.3$ t ha^{-1} cm^{-1}; for a growing season with potential evaporation near 33 cm this corresponds to a total dry matter production of about 10 t ha^{-1} and an efficiency of fixation of solar radiation of 80×10^{-4} (the average for British farming is near 35×10^{-4}). Penman concluded 'The point in these figures is that this efficiency (or the value of k) is a measure of the response to irrigation when irrigation is needed. The better the standard of farming, the greater is the return for added water.' A high standard of farming implies that correct amounts of fertilizers are applied at the most appropriate times and in the best way; that these applications of extra nutrients result in considerable increases in w.u.e. has been proved by large numbers of field experiments made in many countries where irrigation is a common practice.

5. The effects of water on the efficiency of fertilizers

The maximum return from fertilizer dressings, measured in terms of increased crop yields, depends on the crop having sufficient water to meet its consumptive need. In addition, the solubility of nutrients in the soil, and their transport to the roots, depends on satisfactory water status. These benefits from extra water from rain or irrigation may be diminished where added water leaches soluble nutrient ions below the rooting zone, or facilitates other reactions which result in losses of a nutrient, or which diminish the efficiency of the plant in producing extra growth to correspond with the extra nutrients supplied.

5.1. *Problems with nitrogen fertilizers*

Nitrate. This is the form of nitrogen commonly taken up by plants. Fertilizers may supply nitrate or it may be formed by microbial oxidation of ammonium salts, urea, or the N combined in soil organic matter. Nitrate is lost by leaching when water drains through the soil; in waterlogged soil the ion is denitrified by microbial activity to release nitrogen and its oxides to the air. Both leaching and denitrification are responsible for much loss of nitrogen from agricultural systems; while the environmental pollution that is caused in these ways should be avoided, it is also very important to farmers, and to those who purchase their produce, that losses of an expensive input to agricultural systems should be avoided. Minimizing losses requires a good scientific knowledge of soil, cropping system, and climate, so that the recommendations made for applying irrigation water and fertilizer N will not result in nitrate being present when surplus water drains through the soil or at times when waterlogging may occur.

Urea. This now supplies about a third of the world's fertilizer N and it is being increasingly used in the tropics and sub-tropics where irrigation is commonly applied. This fertilizer is subject to other mechanisms of loss. When urea is hydrolysed by the enzyme urease, ammonium carbonate and bicarbonate are likely to be formed; if the reaction takes place on or near the soil surface these salts are likely to decompose and the ammonia released will be lost to the air. Experiments have shown that large losses of ammonia commonly occur in practice. The remedy is to place the urea 10 cm or more below the soil surface so that any ammonia released will be absorbed by soil; when this is done urea can be as efficient as ammonium salts or nitrates for arable crops or grassland. (Losses of ammonia also occur when ammonium salts are spread over calcareous soils with high pH.) When urea is used on crops that are irrigated, the timing of the fertilizer and the amount of water applied must both be carefully planned. If urea is to be broadcast over the soil surface, it should be put on the dry surface and then irrigation should be applied afterwards so that the urea is dissolved and washed sufficiently deeply into the soil. If very large amounts of water are applied it must be recognized that urea is completely mobile and may be washed to depths that roots may not reach. Spreading urea on the moist surface of land that has just been irrigated should be avoided as this gives maximum opportunity for rapid hydrolysis of the urea and consequent loss of ammonia. The risk of loss by leaching was investigated by Singh *et al.* (1984), working in India, where urea supplies 78% of the N used as fertilizer. They found that urea behaves like an unreactive ion such as chloride by moving in soil water before it is hydrolysed. When urea was applied to sandy soils and was immediately followed by irrigation with 5–7.5 cm of water the fertilizer was leached down to about 30 cm, but if rain or irrigation supplied 10 cm or more of water almost all of the urea was leached below the rooting zone in these light-textured soils. It was preferable to place the urea below the soil surface and allow time for the hydrolysis to ammonium to occur before a large amount of water was applied.

5.2. *Increases in the effects of nitrogen fertilizers*

The experiments which Penman (1971) initiated at Woburn provided many examples of the responses to N fertilizers in the presence and absence of irrigation applied to the loamy sand soil with small water-holding capacity. On this soil it was found to be essential to have an adequate supply of water available to secure satisfactory returns from N fertilizer.

Shimshi (1969) described experiments in Israel where a range of rates of ammonium sulphate application was tested on maize which received a range of irrigation frequencies. Fertilizer efficiency was assessed by calculating the relations between moisture stress, the N applied, and the yield of maize. The outcome is summarized in table 4, which shows how irrigation, by reducing moisture stress, more than doubled the efficiency of the N fertilizer (which was assessed by the ratio of kilograms of grain produced per kilogram of N applied).

TABLE 4. THE RELATIONS BETWEEN MOISTURE STRESS AND THE NITROGEN FERTILIZER NEEDED FOR MAXIMUM YIELD OF MAIZE GRAIN AND THE EFFICIENCY OF THE NITROGEN FERTILIZER

(from Shimshi 1969)

moisture stress	maximum yield	nitrogen needed for maximum yield	efficiency ratio (kilograms grain per kilogram N)
atm[a]	t ha^{-1}	kg N ha^{-1}	
0.2	10.3	363	28.4
0.5	9.1	355	25.6
1.0	7.0	336	20.8
1.5	5.1	307	16.6
2.0	3.2	258	12.4

[a] 1 atm = 101325 Pa.

5.3. *Effects of drought on phosphorus uptake*

Day *et al.* (1978) made experiments on barley grown at Rothamsted on a deep soil with a large water-holding capacity. The surface soil contained an amount of soluble phosphate that is quite adequate for barley which receives sufficient water. The relation between grain yield and water use was nearly linear. The effect of drought on yield was, in part at least, a result of its effect on phosphate uptake. In drought-stressed plants the concentration of P was as low as is commonly found in barley grown on P-deficient soils. This was ascribed to a rapid decrease in the uptake of P as the surface soil dried (although reserves of available P in this soil horizon were adequate), and to the lack of reserves of available P in the deeper horizons which continued to supply water.

6. The effects of water status of soil on microbial activity that affects crop nutrition

6.1. *The biological fixation of nitrogen*

Lie (1981) showed that the legume–*Rhizobium* symbiosis is very sensitive to water conditions; both water stress and waterlogging cause damage. Good growth of nodules, and adequate fixation of N, depend on adequate water supply. Prolonged drought causes damage to the nodules; often they are shed from the root. Osmotic damage due to high salt concentrations may also occur in drought. Waterlogging leads to oxygen deficiency which inhibits root growth and also retards nodule development. Excess water surrounding the nodule practically inhibits fixation of N. In some symbioses the nodulated root can adapt to low oxygen tensions; soybeans have this ability.

The amounts of N fixed by grass–clover leys at Rothamsted and Woburn have been given in table 2. Pest control increased the amount of N fixed by Blanca clover which was cut three times a year; irrigation further increased the quantities of N fixed, particularly at Woburn.

6.2. *Other microbiological activities*

The water status of soil regulates the activity of the nitrifying organisms which release inorganic N from soil organic matter. This topic was discussed by Power (1983), who concluded that for practical purposes the rate of nitrification in soil is linearly related to the soil-water content in the whole range from field capacity to wilting point.

Vesicular–arbuscular mycorrhiza (v.a.m.) form symbioses with the roots of many plants and they assist the uptake of nutrients (virtually by extending the root range of the plant); they have notable effects on phosphate nutrition and also on the uptake of micronutrients. Hardie & Leyton (1981) reported work showing that red clover plants infected with v.a.m. have decreased hydraulic resistance, extract water to a lower soil-water potential, and recover turgor faster, than non-mycorrhizal plants. The soil-water potentials at wilting stage were -0.8 to -1.2 MPa for non-mycorrhizal plants, but -1.8 to -2.4 MPa for plants infected with mycorrhiza.

7. The practical management of irrigation and crop nutrition

Methods of irrigation influence the use by crops of nutrient reserves in soils and the efficiency of applied fertilizer. The use of fertilizers in relation to irrigation practice was discussed by Viets *et al.* (1967). But they had to report (in 1967) that few rigid comparisons of the effects of irrigation method on fertilizer requirement had been made. They emphasized the complexities of the problems involved where results depended on crop and soil as well as on the nutrients being considered. Some of the deficiencies in our information have been made good since the work of Viets *et al.*, but much remains to be done on the effects of irrigation system on nutrient efficiency. The evidence we have indicates that drip irrigation may increase the efficiency of both water and fertilizer compared with flood, furrow, or sprinkler irrigation; further comparisons of drip irrigation with other methods are justified on crops where drip application is appropriate. The slender evidence available suggests that subsurface irrigation may have advantages over drip irrigation by establishing more favourable water and nitrogen relations. This method should be further investigated by using suitable crops and sites and also where water is costly and scarce. It is important to recognize that large differences between the efficiencies of fertilizers used with contrasting irrigation systems have been revealed in experiments. Therefore it is important that the results of experiments testing the effects of fertilizers with one irrigation system should not be extended to another system unless appropriate comparisons have been made on the site. More work is needed on the choice of fertilizer salts, and the appropriate concentrations, where fertilizers are applied in irrigation water ('fertigation'). Some of the present evidence is contradictory, particularly on the choice of forms of N.

Kafkafi (1973) discussed the many problems involved in arranging to supply nutrients to irrigated crops; incorrect decisions on fertilizer application could result in reduced yields and waste of the effort expended on irrigation. Efforts must be made to prevent losses of N by leaching or denitrification of nitrate, and by volatilization of ammonia. Potassium may be lost by leaching from soils with low cation-exchange capacities, but not from clay soils. Efficient phosphate uptake requires good regulation of the water supply. Kafkafi discussed the soil and plant parameters, which must be known to plan combined irrigation and fertilization.

7.1. *Experiments with drip irrigation*

Fereres (1983) stated that drip irrigation made uniform fertilizer application possible by applying nutrients in the water. This was important where localized wetting patterns limited uptake of nutrients from soil. For example, where available potassium had been distributed through the surface soil, frequent sprinkler irrigation had resulted in a greater uptake of K than when water was applied by drip, but supplying the K in the drip resulted in satisfactory uptake. The less mobile nutrients can be dispersed through the soil by drip irrigation; in an experiment a dressing of 39 kg P ha^{-1} moved 30 cm deep into clay loam soil when applied by drip – much deeper than a surface application of phosphate would move when water is applied by other methods. Potassium applied by drip will move down even deeper – which benefits fruit trees. Fereres stated that when nitrate is applied by drip there is a risk of denitrification occurring in some soils and ammonium N may then be preferable. But Kafkafi *et al.* (1971) found that the best yields of tomatoes were obtained when potassium nitrate supplied N and K; ammonium N reduced the yields, increased the water requirements, and induced Mg deficiency. They concluded that ammonium ions should be absent from nutrient solutions used for tomatoes grown in sand culture.

Feigin *et al.* (1982) applied drip irrigation for celery and compared ammonium sulphate (AS) and a slow-release (SR) fertilizer, both placed in bands at the centre of the bed before planting, with urea–ammonium nitrate (UAN) solution applied at three rates through the irrigation. (The slow-release material was a resin-coated NPK fertilizer containing 19% N, with equal proportions of nitrate and ammonium). The rate of irrigation had little effect on the percentage uptake of N from the UAN, but the AS and SR fertilizers applied to the soil were less efficient at the larger watering rate and, at comparable rates, they provided less N for the celery than UAN did. Measurements of nitrate in the soil after the celery was harvested showed that deep leaching was more serious with both AS and SR fertilizers than with UAN, leaching was increased by the larger irrigation rate. The final conclusion was important: urea–ammonium nitrate solution applied through the drip irrigation system supplied N more efficiently than either ammonium sulphate or slow-release fertilizer when these were applied to the soil in the normal way.

7.2. *A comparison of irrigation methods in Australia*

Smith *et al.* (1983) reported that there were considerable interactions between the method of irrigation used and applications of N fertilizer in northern Australia. The results of an experiment given in table 5 show that the response by sorghum to N fertilizer was much less when furrow irrigation was used than when water was applied by sprinkler. With furrow irrigation the fertilizer was drilled under the furrows. Before sprinkling, fertilizer was either spread on the flat seedbed, or was drilled under the furrows; the results with these two methods of application of fertilizer seemed to depend on the amount of N applied before sprinkler irrigation. Results with furrow irrigation were consistently inferior at all rates of N to results from sprinkler application of water. The large effects recorded were partly due to the poor seedling establishment and early growth with furrow irrigation which resulted either from deficiency of N, or from salts accumulating at the tops of the hills between the furrows.

TABLE 5. THE EFFECTS OF IRRIGATION METHODS AND OF RATES OF NITROGEN FERTILIZER AND METHODS OF APPLICATION ON YIELDS OF SORGHUM GROWN ON CLAY SOIL IN THE ORD RIVER SCHEME, NORTHERN AUSTRALIA

(from Smith *et al.* 1983)

experimental treatments		nitrogen fertilizer applied/(kg N ha^{-1})			
irrigation	fertilizer application	0	80	170	340
		yields of grain/(kg ha^{-1})			
sprinkler	on flat seedbed	3374	7318	7997	9142
sprinkler	under furrow	3542	6903	8737	8512
furrow	under furrow	3017	4855	6806	5261
		plant establishment (plants m^{-2})			
sprinkler	on flat seedbed	36	34	31	32
sprinkler	under furrow	30	33	34	35
furrow	under furrow	31	27	27	16

These results are important and emphasize the need for more experimentation to compare fertilizer application with different irrigation systems. Smith *et al.* state that surface flood and furrow methods are used on 76% of irrigated land in Australia. Water is applied to land by spray on only 20% of the whole irrigated area and drip irrigation is rare.

7.3. *Subsurface irrigation*

This method of irrigation is the most recent to be developed scientifically. Criddle & Kalisvaart (1967) described sub-irrigation systems as they were used about 20 years ago. Often sub-irrigation was effected through existing drainage systems; such methods had been extensively used in the Netherlands and had been successful in Florida. The method was also used in some semi-arid and arid regions of the U.S.A. They believed that this system, if properly designed and operated, might prove to be the best method for many areas. Other authors have emphasized the value of subsurface irrigation for high-value crops and where water is scarce, as both water and fertilizer efficiencies are superior to those achieved by other methods and less power is needed to operate the system.

In recent work Mitchell & Sparks (1982) compared trickle (drip) irrigation and subsurface irrigation in a five-year period of experiments on maize grown on loamy sand soil in Delaware. The tubing for the subsurface system, in lines 33–36 cm deep, functioned satisfactorily for five years. Both irrigation methods increased yields and subsurface application of water was more effective. It was suggested that the poor performance of trickle irrigation relative to subsurface irrigation was a result of nitrogen deficiencies that occurred with trickle irrigation and that were confirmed by leaf analysis. The same amount of water was applied by the two irrigation methods; the poorer results with trickle irrigation were ascribed to losses of nitrogen owing to leaching or denitrification or both. The authors concluded that more favourable water and nitrogen relations could be established when subsurface irrigation was used.

8. The needs for future research and development

The exploitation of our present information on the water–nutrient interaction in crop production will greatly benefit farmers and those who consume the food that is produced in agricultural systems, by increasing the crop yield produced by a unit of water and by a unit of plant nutrient. Further experimentation is required to refine our knowledge and to extend it to farming systems in the regions where irrigation is now used or where its introduction will be justified. The application of the present knowledge by improved advice to farmers has tended to lag behind the research programmes and this aspect requires very serious attention.

8.1. *The kinds of research work that are required*

The main need is for more field experimentation, but associated physiological and pathological work on crops, and chemical and physical work on soils, will also be required. Some topics which appear to need further investigation are noted below:

Multidisciplinary field experiments should be established on a long-term basis. They should include factorial tests of a range of water and fertilizer applications. In addition, where other constraints, such as pests and diseases, are identified, inputs to control them must be included in the factorial scheme of experimental treatments. Individual nutrients, and their factorial combinations, may need to be tested. Contrasts of times and methods of irrigation and of fertilizer application should be included in the experiments. These experiments will provide the field basis for the lines of work that are listed below.

The form of the nutrient–water interaction needs further investigation.

Root–soil relations require more study. This work will involve the role of nutrient reserves in soil, their solubility and movement to and uptake by the roots, as these factors are influenced by water status.

Physiological work on crops is needed to show how the nutrients and water jointly affect growth processes and yield components of the crop. An extension of physiological work on the effects of ions provided by fertilizers on osmotic processes in the plant, and on stomatal regulation, will be important; there should be special emphasis on the role of potassium, and also on that of nitrogen.

8.2. *The interpretation and application of the results of investigations on the water–nutrient interaction*

Maximum use should be made of the results of research on this interaction by developing improved recommendations for farmers which are expressed in ways that they can understand and apply. The activities needed to secure satisfactory development are noted here:

The results of all relevant experiments made in a region on the nutrient–water interaction should be assembled and discussed so that the effects of crop, soil, and climate on w.u.e. as it is affected by fertilizers may be compared. (Penman (1971) gave a lead to this topic, noted in §4.2, which is worth following to a logical conclusion.)

Models of the crop production process, including all relevant soil, climate, and crop parameters, should be developed. The models should be relevant to each of the agricultural systems considered as a whole, and they must be validated by using the results of local experiments (the model is no substitute for experimental work!). From the main model more detailed models of the nutrient–water interaction for particular crops and localities should then be developed. The models will also be involved in establishing the databases from which recommendations for particular sites and crops will be developed.

The final task will be to set up a basis from which extension workers will provide recommendations to individual farmers on the amounts and forms of fertilizers that will be justified economically, on the best methods and times for applying them in relation to the needs of the crop, and the timing and method of irrigation that will be applied. Developing this advice will require the use of the local model for the water–nutrient interaction and the scientific information that extension workers will have on the fertility characteristics of the soil and the water status of crops and soils.

In connection with this last point it is appropriate to commend an initiative by Prihar (1983) in India. He gave an account of five years of work with wheat which showed how the optimum rate of application of N fertilizer varied with the water supply available to the crop. An equation showing how yield was related to total water supply was used to plot the relation between the rates of application of N fertilizer and of water supply. An example of the result of this work is shown in figure 2 where 'marginal productivity' (expressed as kilograms of grain produced per kilogram of N applied) at different levels of available water is plotted against the amount of N applied. Prihar states that such plots would permit rational decisions to be made to guide farmers on the rate of nitrogen to be used for a given level of water supply, taking account

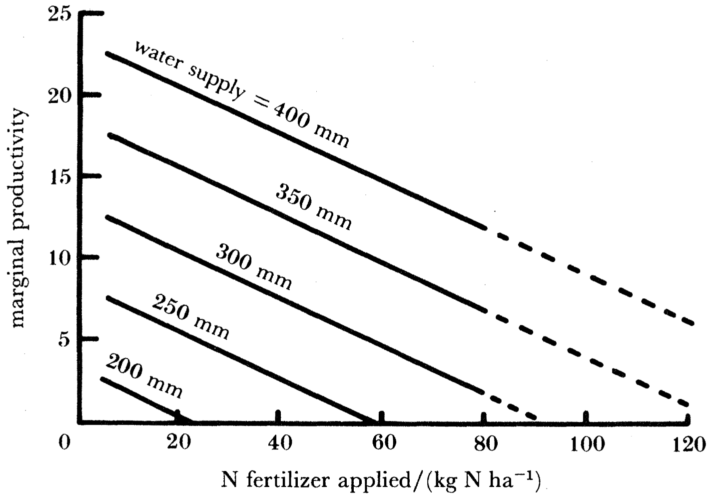

FIGURE 2. The marginal productivity (expressed as kilograms of grain produced per kilogram of N applied) of wheat as affected by the amount of nitrogen fertilizer applied and the total amount of water available to the crop. From Prihar (1983).

of the marginal productivity at which the farmer wished to operate. He stated that 'Information of this type is utterly lacking and need to be generated for other regions so as to rationalize the use of fertilizers for dryland crops.'

8.3. *The way forward*

The scientific development of irrigated agricultural systems requires more research on the interaction between nutrients and water supply, and the application of the results of the research to practical conditions. At the end of his paper (published 135 years ago), to describe the first research made in Britain to investigate this interaction, Lawes (1850) made a plea for support for research on this topic which scientists considered to be necessary so that progress could be made with agricultural development. The final sentence of his paper is relevant to this paper. He wrote: 'Results of this kind promise, it is true, but little prospect of immediate and practical application, but by their aid the uncertain dictates, whether of common experience, theory, or speculation, may, ere long, be replaced by the unerring guidance of principles; and then alone can it reasonably be anticipated that miscellaneous and departmental analyses may find their true interpretation, and acquire a due and practical value.'

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