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Physiological Basis of Yield Improvement of Arid Zone Crops through Nutrient Management

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ABSTRACT

About 62% of Indian arid zone lies in western Rajasthan where low annual rainfall and its erratic distribution result in widespread and recurring droughts of varying intensity and magnitude. Crops in the arid and semi-arid areas suffer from both moisture and nutrient stresses. As nutrient and water requirements are intimately linked therefore, the interaction between soil moisture deficits and nutrient uptake that is of paramount importance has been extensively studied. Our investigations have established significant positive response of plants of these zones to improved soil fertility. However, the degree of yield response varied with rainfall pattern, drought intensity and crop species. Advantages of fertilizer application under arid conditions might be realized in situations where both dry and wet phase exist during the growing period. However, the benefits of nutrients under such conditions are generally less than in well irrigated crops. Fertility-induced metabolic efficiency coupled with higher photosynthetic and nitrate reductase activity are considered to be the control mechanisms for enhanced growth and yield of rainfed crops. Studies suggested that tissue hydrature was not an infallible index of metabolic efficiency as nutritional status of plants was more critical under water deficits for leaf metabolism, photosynthesis, growth and yield in different crops where nitrogen moisture interactions were explored. Alleviation of drought effects in arid legumes has been achieved through phosphorous (P) application which favourably modulates various physiological and biochemical processes. Similarly, applied potassium (K) mitigates the adverse effects of water stress by favourably influencing internal tissue moisture, photosynthetic rate and nitrogen metabolism in legumes. Thus, significant yield improvement can be obtained even under low soil moisture conditions through adequate nutrient management.

Keywords: carbohydrate metabolism, nutrient uptake, plant nutrition, soil fertility, water stress

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INTRODUCTION

Indian agriculture continues to be a gamble of the vagaries of monsoon, rainfall being most critical because nearly 70% of the net sown area is still rain dependent. Low and poor rainfall distribution, delayed onset of monsoon and prolonged dry spells during the cropping season, often results in water stress conditions at different growth stages causing decline in productivity and some times even crop failures. The severity of drought depends on the duration, frequency, intensity and geographical distribution of rainfall of a region besides several other factors. In this regard, arid region of Rajasthan is a frequent victim of disastrous droughts, resulting in huge economic losses and degradation of natural resources of the region.

Besides arid climates, the soils of arid regions have a number of constraints for sustainable land use and crop production. In addition to low water holding capacity, poor water availability, arid zone soils have low organic matter and are deficient in nitrogen. Low amount of organic matter has been attributed to high temperature, low rainfall, scanty vegetation cover and sandy texture of soil (Praveen-Kumar *et al*. 1998). The available phosphorus content varies widely in different soils and mean content is less than 20 kg ha^{-1}. However, soils of arid region are generally well supplied with potassium (Joshi 1993). Furthermore, decreasing water availability under drought generally results in reduced total nutrient uptake and frequently reduced concentration of mineral nutrients in crop plants, having adverse effects on crop yields. Water stress or drought can also interfere with nutrient distribution to seed resulting in poor seed quality. Thus, management of nutrient uptake under drought condition is of great importance for sustainable plant productivity.

The crop yields in arid regions are low compared to the humid and sub-humid regions, mainly due to deficiency of water. The crop production is totally dependent on low and erratic rainfall. Hence, the most obvious priority is to achieve maximum production of an economic yield per unit of available water. Besides several agronomic practices, soil fertility management is crucial as poor fertility of the arid soils is a major limitation to increasing crop yields. The positive response of important *Kharif* crops to applied fertilizer (mainly N and P_2O_5) is well known (**Table 1**). However, it has been found to vary with soil type, seasonal rain-

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Invited Review

Table 1 Average response of *Kharif* crops to nitrogen and phosphorus application. Data modified from Narain *et al.* (2000).

Crops	Average response	
	Kg grain kg^{-1} N	Kg grain kg^{-1} P
Pennisetum glaucum	13.5	8.0
Sorghum bicolor	23.4	30.7
Sesamum indicum	3.2	2.1
Cyamopsis tetragonoloba	-	8.7
Vigna radiata	-	6.6
Vigna mungo	-	4.3

Table 2 Impact of drought on food production in Rajasthan (India) and western arid part of the State in the year of drought against the previous good rainfall year. Data modified from Narain *et al.* (2006).

Years	Food grain production (million tonnes)	
	Rajasthan State	Western arid area
1983 – 1984	11.50	4.57
1987 – 1988	6.03 (47.6)	1.38 (69.8)
2001 – 2002	17.13	6.88
2002 – 2003	9.26 (45.9)	3.44 (50.0)
2003 – 2004	10.90	6.52
2004 - 2005	5.53 (49.3)	2.96 (54.6)

Figures in parenthesis indicate percent decrease due to drought against the previous good monsoon year

fall during the growing season and growth stage of the crops. As nutrient and water requirements are intimately linked and fertilizer application increases water use efficiency, therefore, the interaction between soil moisture deficits and nutrient uptake is of paramount importance and a subject of extensive studies. Our investigations on this subject have further gone to higher level encompassing physiological and biochemical processes, which are directly or indirectly modulated by plant nutrients. The present review is an attempt to coordinate and correlate the complex nutrient-moisture interaction not only at the plant performance or crop yield level, but also at the metabolic plane to have a clear understanding of the processes involved in yield improvement through nutrient management.

DROUGHT SCENARIO IN INDIAN ARID ZONE

According to the National Commission of Agriculture (1976), if the drought occurs in more than 40% of the years in an area, it is classified as chronically drought prone area. As per this classification, Indian arid zone is a chronically drought prone area. Analysis of rainfall data (1901-1999) indicates that out of 99 years, the Indian arid zone experienced agricultural drought in one part or the other during 33 to 46 years, which suggests a drought once in three years to alternate years (Narain *et al.* 2000). Often drought prolong continuously for 3 to 6 years, in this region as during 1903-05, 1957-60, 1984-87 and 1997-99. Such prolonged droughts put tremendous stress on natural resources and lead to severe scarcity of food, fodder and water.

About 62% of the arid zone in India (covering an area of about 20 million ha), lies in Western Rajasthan, forming the principal arid zone of the country. Low annual rainfall, which varies from 400 mm in the eastern part to less than 100 mm in the westernmost part and its erratic distribution results in widespread and recurring droughts in many parts of the region with variation only in its magnitude from year to year (Narain *et al.* 2006). Added to this decreased rainfall gradient, the year-to-year variability increase from 40% in the east to 70% in the west. Therefore, droughts and disastrous famines are recurring features of the Indian arid zone (Rao 1997; Rao and Singh 1998).

The major causes of drought in the Indian arid zone are its geographic location not favouring abundant monsoon rainfall, poor quality and excessive depth of groundwater, absence of perennial rivers and forests, poor water holding capacity of soils and huge withdrawal from limited groundwater resources. Furthermore, the increased pressure of both human (19.8 million) and livestock (28.0 million) population has put tremendous pressure on land and limited water resources. Therefore, the impact of drought is felt much more severely in the arid region compared to other parts of the country (Narain *et al.* 2000, 2006). Migration in search of fodder, food, work and water is a common feature imposing hardships upon desert dwellers, causalities of livestock and famines in extreme drought situations.

Food production particularly in the state of Rajasthan nose-dives during the years of drought and aberrant weather. Severe droughts reduced the food grain production in western Rajasthan by 70% during 1987-88, 50% during 2002-03 and again by 55% during 2004-05, against previous good monsoon year (**Table 2**). Such reduction in food grain production was also noticed at the state level also, during drought years. In an agricultural dependent country like India, once the agriculture production declines due to drought, it sets in a chain reaction leading to lower availability of commodities, lower purchasing power and economic growth.

Sustainable strategies must be developed to alleviate the impact of drought on crop productivity. In areas of recurring drought, one of the best strategies for alleviating drought stress is the choice of crop and varietal manipulation, through which drought can be avoided or its effects can be minimized by adopting varieties of short duration crops that either escape drought or are tolerant. If the drought occurs during the middle of a growing season, corrective measures can be adopted which vary from reducing plant population to fertilization or weed management. A good rainfall event can be fruitfully harvested by collecting rain in farm ponds or tanks than can be recycled as life saving irrigation during a prolonged dry spell. In fact, all such strategies are location, time, crop and socio-economic conditions specific.

NUTRIENT AVAILABILITY AND UPTAKE UNDER WATER DEFICITS

Nutrient uptake by plants depends on ion concentrations at the root surfaces, root absorption capacity and plant demand. After uptake by roots, nutrients are transported to the various plant organs for utilization in different metabolic processes. Thus, nutrient uptake by plants involves several interconnected processes such as, (a) nutrient release from the soil solid phase to solution, (b) transport to roots for absorption, and (c) translocation and utilization in plants. These processes are influenced largely by soil, climatic and plant factors. Water deficits generally reduce plant growth and yield. It is well known that much of the reduction in growth is associated with reduction in turgor and cell wall development. However, it appears unlikely that turgor can be considered the sole key to the general response. Vaadia and Waisel (1967) reported that reduced mineral nutrient availability significantly contributes to poor growth under conditions of decreasing water availability in the soil. Viets (1972) concluded that decreasing water availability culminating in plant-distress symptoms associated with drought, results in reduced total nutrient uptake and frequently in reduced concentrations of mineral nutrients in plant tissues. Although ion and water absorption by the root from soil solutions are independent, but in soil they are intimately and complexly linked because of the dominance of water availability on all microbial, physical and physiological processes.

The quantity of water in the soil affects not only the amount of nutrient in the soil solution, but also the rate of movement to the root by diffusion and mass flow as water is absorbed by the root. Most of the experimental data indicates that most important effect of water deficits is on transport of nutrients to the root and on the root extension (Viets 1972; Fageria *et al.* 1991). Olsen *et al.* (1961) showed that ^{32}P uptake by corn was proportional to water content in different types of soil. Water stress, in general, reduces nutrient uptake by roots and transport from roots to shoots because of restricted transpiration rate and impaired active transport and membrane permeability (Erlandsson 1975). A decline in the soil moisture is associated with a decrease in the diffusion rate of nutrients from the soil matrix to the absorbing root surface. Plant water status and internal water deficits are related to root system development and during water stress root permeability may change to substantially low levels. Inadequate water and nutrient uptake due to reduced root permeability causes a disturbance in root metabolism. Changes in the soil moisture regime can alter root morphology and anatomy, pore size distribution and the angle of root penetration, which affect root proliferation.

It is difficult to clearly delineate the effects of water stress on nutrient uptake and accumulation in plants as both decreases and increases in nutrient element concentrations have been reported with increased water stress (Eck and Musick 1979; Vyas *et al*. 1985; Alam 1994). Although water stress exhibited variable effects on mineral uptake but most studies reported that nutrient uptake decreased with increase in water stress (Garg *et al*. 1984; Kathju *et al.* 1990; Vyas *et al*. 1995, 1999). It is generally agreed that uptake of P by plants is reduced in dry soil (Viets 1972; Alam 1994). Several plants subjected to water stress had markedly low concentrations of Ca, K and P (Brown *et al.* 1969). The values for relative P uptake by maize plants under stress were 100, 94, 80, 54 and 35% of the control at the water stress levels of -0.3, -0.5, -1, -3 and -9 bars, respectively. However, there are genetic variations within species for their response to mineral uptake. These variations may explain some of the differences that are attributed to reduced availability of nutrients under water stress conditions (Reddy *et al*. 1980). For example, the relative amounts of K, Ca and Mg increased more in barley (*Hordeum vulgare*) than rye (*Secale cereale*) when water stress was imposed. Contrarily, in soybean (*Glycine max*) plants, uptake of N decreased under water deficits which was attributed to the decreased transpiration rate to transport N from roots to shoots.

Vyas *et al.* (1985) reported that concentration of N consistently increased in sesame (*Sesamum indicum*) plants with increasing intensity of water stress but that of P decreased progressively (**Fig. 1**). However, the uptake of both the nutrients declined significantly due to reduced growth. Similar responses have been reported in wheat (*Triticum aestivum*; Kathju *et al.* 1990) and Indian mustard (*Brassica juncea*; Vyas *et al*. 1995).

Viets (1972) generalized that moisture stress induces definite increases in N levels, a decrease in the P level and variable effects on the K level. In all grasses, however, a definite reduction in the K level with moisture stress was also observed in addition to the increase in the N and the decrease in the P level. In mature maize plants grown with inadequate moisture, accumulation of P, N, Mg, K and Ca was 40, 50, 65, 71 and 91%, respectively, of those found in plants grown with adequate water. The uptake of mineral elements was found maximum when the water potential was near that of the field capacity or about -0.03 MPa.

Increased water stress not only decreased the uptake of nutrient elements but also increased Ca/P and Ca/K ratios. Under water stress conditions, root system altered structurally and functionally could supply nutrients exclusively by more active root tips. This led to a low uptake of anions and greater uptake of divalent cations compared to monovalent cations. Thus, abnormal Ca/P and Ca/K ratios developed in the plant may cause other complications in the growth of plants (Alam 1994).

In conclusion, mineral uptake is frequently reduced in drought-stressed plants. Reduced absorption of inorganic nutrients can result from interference of nutrient uptake and unloading mechanism besides reduced transpiration flow (Bradford and Hsiao 1992). One of the earliest signs of drought stress is in the translocation of P from older leaves to the stems and meristematic tissues. Translocation of N closely follows that of P, suggesting the occurrence of protein hydrolysis and alteration of normal cell function. Water stress can also interfere with nutrient distribution to seed resulting in poor seed quality. Thus, management of nutrient uptake under water stress conditions is of paramount importance for sustainable plant productivity.

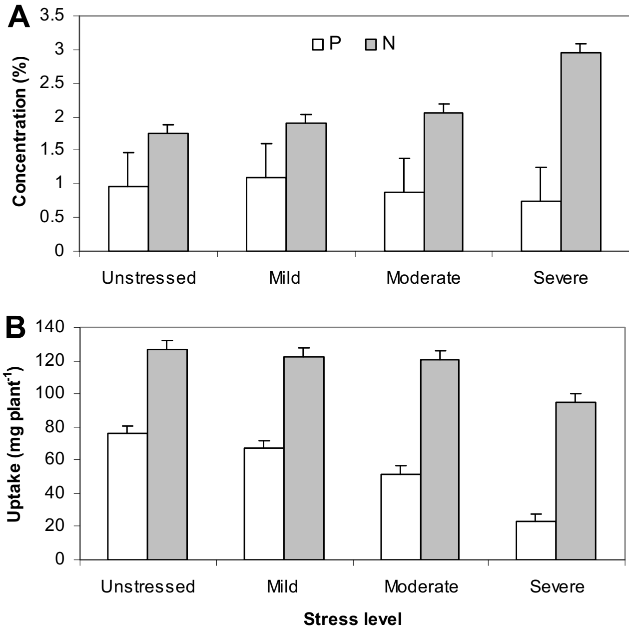

Fig. 1 Influence of water stress intensities on the concentration (**A**) and uptake (**B**) of nitrogen and phosphorus in sesame. Figure drawn from data in Vyas *et al.* (1985).

CROP RESPONSES TO NUTRIENT SUPPLY UNDER MOISTURE STRESS

Rainfed agriculture in the arid and semi-arid regions of India is greatly influenced by water shortage caused by low, highly variable and erratic rainfall. However, apart from water deficits, crop productivity in these regions is also affected by low soil fertility. Thus, rainfed regions face the twin problems of 'water thirst' and 'plant nutrient hunger'. Due to moisture scarcity, these lands are incapable of supporting double cropping. Consequently, the soil organic matter turnover and fertilizer use efficiency is very low. However, in order to sustain the productivity of arid zone crops, it is very important to offset the nutrient depletions through appropriate fertilizer management practices.

The soils of arid region are generally coarse-textured and deficient in organic matter as well as N content (Joshi 1993). Mean organic C content in the arid soil range from 0.05 to 0.2% in coarse, 0.2 to 0.37% in medium and 0.3 to 0.4% in fine-textured soils. Low clay content, hot climate and low rainfall are mainly responsible for low organic carbon (Praveen-Kumar *et al.* 1998). These soils contain total N in the range of 0.002 to 0.005% and available P varies from 5.4 to 8.5 kg ha^{-1} (Aggarwal and Lahiri 1981). However, soils of arid regions are generally adequate in K and total K content varies from 0.54 to 1.57%. Thus, there is a need to improve productivity with adequate nutrient management practices.

Most of the crops grown in the region such as, pearl millet (*Pennisetum glacum*), clusterbean (*Cyamopsis tetragonoaloba*), moth bean, (*Vigna aconitifolia*) mung bean (*Vigna radiata*) and sesame during *kharif* season and wheat and mustard during *Rabi* season respond very effectively to nutrient application. Though, it is generally agreed that response to applied nutrients by rainfed crops is not assured and sometimes may not be profitable unless proper soil moisture is available. Nevertheless, nutrient management is of prime importance in the region. Kathju *et al.* (1987) reported that N use efficiency in pearl millet and sesame

Table 3 Influence of N fertilization on grain yield and water use efficiency (WUE) of pearl millet genotypes. Data modified from Kathju *et al.* (2001).

Category	Grain yield (kg ha^{-1})			WUE (kg ha^{-1} mm^{-1})		
	N_0	N_{80}	%	N_0	N_{80}	%
Hybrids	1042 ± 74	1595 ± 22	53.0	3.59 ± 0.27	5.36 ± 0.07	49.3
Composites	1029 ± 59	1479 ± 34	43.7	3.58 ± 0.22	4.89 ± 0.06	36.6
Land races	1206 ± 58	1616 ± 25	33.9	4.07 ± 0.23	5.19 ± 0.11	27.5

Data mean of two years for two genotypes under each category

Table 4 Influence of N fertilization on dry matter and grain yield of pearl millet genotypes under sub and supra-optimal rainfall conditions. Data modified from Garg (2003).

Rainfall character	Average seasonal rainfall (mm)	Average dry matter (kg ha^{-1})		Average grain yield (kg ha^{-1})	
		N_0	N_{80}	N_0	N_{80}
Sub-optimal (< 300 mm)	224	2428.5 ± 108.6	3687.8 ± 176.4	460.3 ± 39.4	677.0 ± 51.3
Supra-optimal (>360 mm)	440	6089.3 ± 100.9	7764.6 ± 242.5	2569.0 ± 137.3	3158.0 ± 94.2

was 7.5-18.0 kg ha^{-1} and 4-14.7 kg ha^{-1}, respectively, while P use- efficiency in clusterbean, mung bean and moth bean was 4.2-5.3, 1.4-4.1 and 0.1-0.9 kg ha^{-1}, respectively. Thus, adequate nutrient supply is pre-requisite for obtaining sustainable yields.

Our investigations on arid zone crops have established significant positive response of plants to improved soil fertility, particularly N and P (Garg *et al.* 1984; Vyas *et al.* 1987; Kathju *et al.* 2001; Garg 2003). However, the degree of yield response varied with rainfall pattern, intensity of drought, native soil fertility and crops species. On the basis of various experimental data obtained on sandy soils, it has been found that advantages of fertilizer application under arid conditions may be realized in situations in which dry and wet phase exist during the growing period (Lahiri 1980; Garg 2003). However, the benefits of nutrients under such drought conditions are likely to be less than in well irrigated crops.

Nitrogen plays an important role in improving the yield of cereals, but in legumes it is required as a starter dose. Application of 80 kg ha^{-1} proved superior to 40 kg ha^{-1} and resulted in a 72% increase in grain yield of pearl millet (Parihar *et al.* 1998). In another study, N application up to 80 kg ha^{-1} in pearl millet increased yield in good rainfall years, but in drought years, significant effect was not observed beyond 40 kg N ha^{-1} (Aggarwal and Praveen-Kumar 1996). Garg *et al.* (1993) also reported similar benefits of N fertilization in millet crop during both good and low rainfall years under varying plant density. Kathju *et al.* (2001) reported N-fertilization-induced significant improvement in grain yield and water use efficiency of pearl millet genotypes under rainfed conditions (**Table 3**). The fertilizer induced percent increase was more in hybrids compared to composites or land races with respect to both grain yield and WUE. The fertility-induced higher photosynthesis and leaf metabolic efficiency coupled with higher nitrate reductase activity was found to be responsible for such significant grain yield and dry matter production (DMP) as well as water use efficiency (WUE) and harvest index of the crop. Furthermore, one supplemental irrigation coupled with 80 kg ha^{-1} N fertilization to pearl millet (**Fig. 2**) and sesame crops showed significant additive effects on their yields (Kathju *et al.* 1993; Vyas *et al.* 1999).

Field studies conducted with pearl millet during the years 1990 to 1996 under rainfed conditions of Jodhpur, Rajasthan, India revealed that N application enhanced grain yield and dry matter production (**Table 4**) to varying extent due to variation in rainfall. However, the positive response to N-fertilization was consistently higher in supra optimal compared to sub-optimal rainfall year. The increase was due to higher nutrient uptake, better N partitioning and more efficient metabolism and higher photosynthetic rates (Garg *et al.* 1993; Garg 2003; Kathju *et al.* 2001).

It has been observed consistently in various studies that tissue hydrature was not an infallible index of metabolic efficiency as nutritional status of plants was equally important under water limited conditions for leaf metabolism,

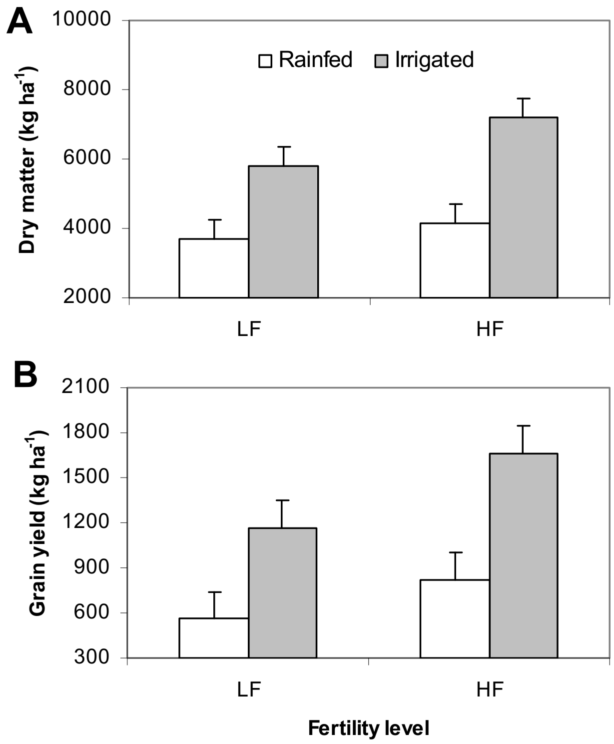

Fig. 2 Influence of low (LF) and high (HF) soil fertility and supplemental irrigation on dry matter (**A**) and grain yield (**B**) of pearl millet. Figure drawn from data in Kathju *et al.* (1993).

plant growth and yield (Garg *et al.* 1984, 1993; Kathju *et al.* 1993; Vyas *et al.* 1995; Kathju *et al.* 2001; Vyas *et al.* 2001). Garg *et al.* (1984) reported that fertility induced alleviation of growth and yield in wheat under two successive cycles of drought at various developmental stages (**Fig. 3**). This was related to large root growth, greater post-drought nutrient uptake and not to any favourable tissue water modulations. Kathju *et al.* (1990) also reported that fertility induced improvement in dry matter and yield of wheat under different intensities of drought at vegetative, flowering and grain filling stages which were attributed to higher nutrient uptake, higher nitrate reductase (NR) activity and better metabolic efficiency. Similar observations were made in Indian mustard where nitrogen application was applied which promotes seed yield under varying moisture levels on variable stored soil moisture regimes (Vyas *et al.* 1995; Garg *et al.* 2001). Burman *et al.* (2003) reported significant positive interaction of nitrogen and sulphur application on seed yield of Indian mustard grown under a gradient of soil moisture created by line source sprinkler system (**Table 5**). This was primarily due to positive and additive effect of the nutrients on photosynthetic rate (**Fig. 4**) and other metabolic processes (Burman *et al* 2003).

Nitrogen application not only improves the yield of

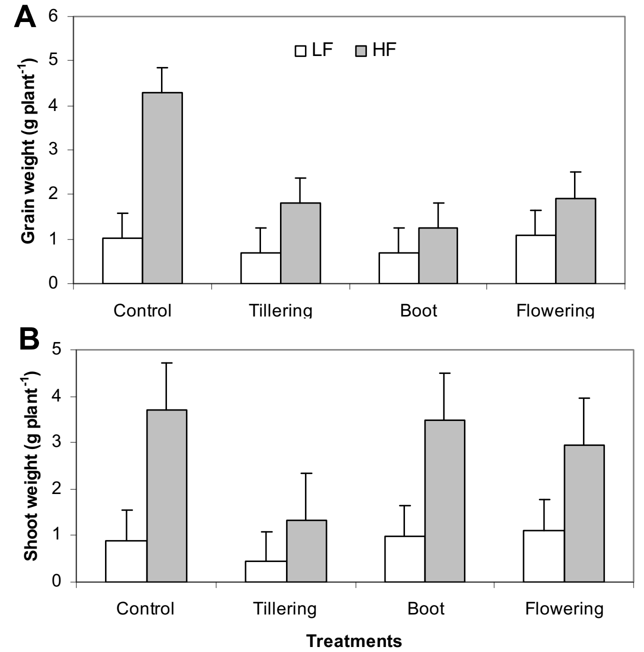

Fig. 3 Influence of low (LF) and high (HF) soil fertility on grain yield (**A**) and shoot dry matter (**B**) of wheat under two successive cycles of drought at tillering, boot and flowering stages of growth. Data modified and re-drawn from Garg *et al.* (1984).

Table 5 Interactive effects of (N) sulphur (S) and moisture levels (M) on seed yield and dry matter of Indian mustard. Data modified from Burman *et al.* (2003)

Treatments	Seed yield (kg ha^{-1})	Dry matter (kg ha^{-1})
Nitrogen (kg ha^{-1})		
0	410	1680
60	935	3643
LSD (0.05)	71	212
Sulphur (kg ha^{-1})		
0	629	2550
30	706	2773
LSD (0.05)	71	212
Moisture levels (mm)		
M1 (310.4)	949	3625
M2 (261.5)	839	3321
M3 (205.2)	774	2990
M4 (147.2)	600	2398
M5 (91.4)	202	974
LSD (0.05)	81	239

cereal and oil seed crops but also has marked influence on the performance of legumes in arid region. Several workers have reported the positive response of legumes to N application on different growth parameters and seed yield (Yadav *et al*. 1990; Singh *et al*. 1993).

Burman *et al*. (2007) found that application of nitrogen (20 kg ha^{-1}) in association with P (20 and 40 kg ha^{-1}) significantly enhanced the seed yield, DMP, and WUE of clusterbean under rainfed conditions of Jodhpur in a two-year study (**Fig. 5**).

The amount of added P becomes less available to plants in arid soils (0.87 to 1.35 g P 100 g^{-1} of soil). Phosphorus plays an important role in stimulating seed setting, hastens maturity and helps in development of extensive root system besides favourable condition for nodulation and nitrogen fixation in legumes. The physiological roles of P in leaf area development, photosynthesis and energy metabolism are well documented (Singh *et al.* 1997; Gutierrez-Boem and Thomas 1998, 1999; Singh and Sale 2000). In this regard a number of our investigations have also revealed significant improvement in seed yield of various crops and legumes by P application under moisture deficient or rainfed conditions

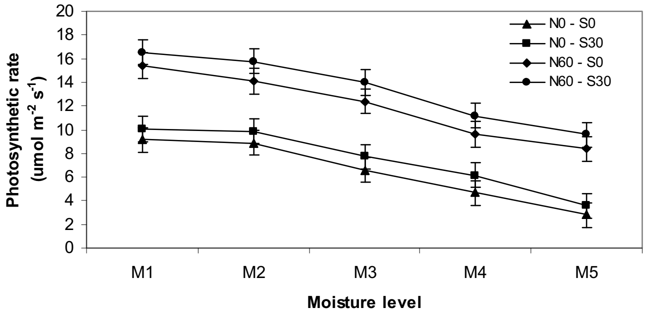

Fig. 4 Interactive effects of nitrogen and sulphur on net photosynthetic rate of Indian mustard grown under different moisture levels. Figure drawn from data in Burman *et al.* (2003).

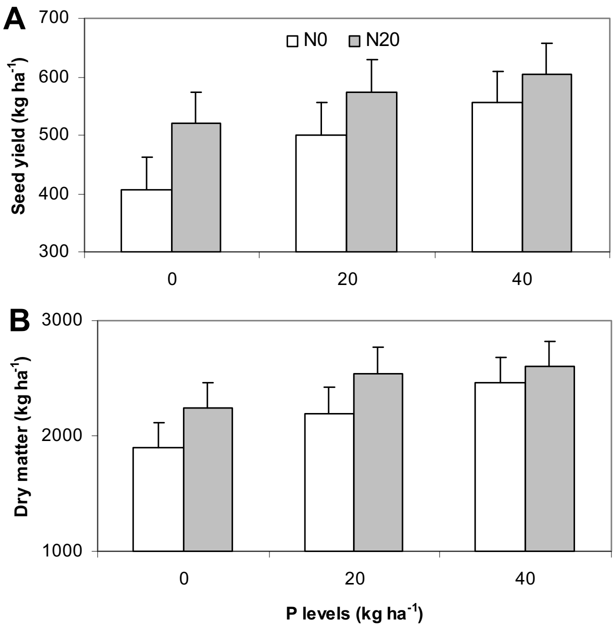

Fig. 5 Interactive effects of nitrogen and phosphorus application on seed (**A**) and yield dry matter (**B**) of clusterbean under rainfed conditions. Data modified and drawn as figure from Burman *et al.* (2007).

Table 6 Effect of drought and phosphorus nutrition on certain metabolic parameters and seed yield of moth bean (mean of four genotypes) under control (C) and drought (D) conditions. Data modified from Garg *et al.* (2004).

Parameters	Stress level	P levels (kg ha^{-1})		% increase
		0	40	
Photosynthetic rate	C	9.67 ± 0.09	11.42 ± 0.19	18.1
(μmol m^{-2} s^{-1})	D	5.44 ± 0.07	6.80 ± 0.12	25.0
Chlorophyll	C	8.25 ± 0.07	8.83 ± 0.12	7.0
(mg g^{-1} dw)	D	7.16 ± 0.11	7.90 ± 0.08	10.3
Soluble protein	C	36.8 ± 1.2	39.7 ± 1.3	7.9
(mg g^{-1} dw)	D	32.9 ± 0.91	36.4 ± 0.89	10.6
NRA	C	119.5 ± 2.9	125.7 ± 3.0	5.2
(μg NO_2 g^{-1} dw h^{-1})	D	38.2 ± 1.8	60.5 ± 2.0	58.1
Seed yield	C	2.57 ± 0.11	2.90 ± 0.15	12.8
(g $plant^{-1}$)	D	1.53 ± 0.05	1.96 ± 0.07	28.0

of Indian arid zone (Kathju *et al.* 1987; Burman *et al.* 2004; Garg *et al.* 2004, 2007; Burman *et al.* 2009). P nutrition has been found to significantly increase leaf area, net photosynthetic rate, chlorophyll, starch, protein contents and activity of nitrate reductase of moth bean genotypes under drought (**Table 6**). Furthermore, application of P was observed to enhance drought tolerance under different intensities of water stress in clusterbean (Burman *et al.* 2009) and moth bean genotypes (Garg *et al.* 2004).

NUTRIENT-MOISTURE INTERACTION ON METABOLIC PROCESSES

The interaction between soil moisture deficits and nutrients has been most extensively studied, showing that nutrient and water requirements are intimately linked and that nutrients increase the efficiency with which crops use the available water (Viets 1972; Lahiri 1990; Arnon 1992; Vyas *et al*. 1995; Kathju *et al*. 2001; Garg 2003). A number of investigations in arid and semi-arid areas in India and elsewhere have established a significant positive response of crops to improved soil fertilization. However, the physiological and biochemical mechanisms involved in nutrient-moisture interaction have received relatively less attention.

Soil moisture deficits adversely influence the leaf metabolism, physiological processes and thereby growth and yield of plants through changes in the internal tissue moisture status. The diverse metabolic derangements are reported to increase with increasing stress intensity (Vyas *et al.* 1985; Kathju *et al.* 1990; Garg *et al.* 2001). However, various studies have consistently indicated that nutritional status of plant even under water limited conditions, plays a critical role in yield enhancement of almost all crops, though degree of improvement may vary with stress intensity, stage of growth and other environmental conditions. After uptake by roots, nutrients are transported to various plant organs for utilization in different physiological and biochemical processes (Fageria *et al.* 1991), which are influenced by soil, climatic and plant factors.

During the last two decades the mechanism of moisture-nutrient interaction has been thoroughly explored in various arid zone crops. Only few of significant finding are briefly outlined here.

Some of the factors conducive for fertilizer-induced improvement in yield include (a) a higher transpiration rate at post-drought stage and as a consequence higher nitrate uptake (Lahiri and Kharbanda 1965), (b) fast post-drought normalization of nitrate reductase activity particularly under high level of soil N (Kathju *et al.* 1990; Lahiri 1990; Garg *et al*. 2001), (c) fast restoration of N metabolism associated with fast normalization of protein-N in the tissue during recovery from stress (Lahiri and Singh 1968; Garg *et al.* 1984), (d) unaltered N uptake under different soil moisture regimes except under acute stress (Lahiri and Singh 1970; Garg *et al*. 1984), (e) maintenance of higher efficiency of leaf metabolism, enzymes activities and photosynthetic rates in fertilized than unfertilized plants under different intensities of drought (Garg *et al*. 1984; Kathju *et al.* 1990, 1993, 2001; Garg *et al*. 2004; Burman *et al*. 2009), (f) the improvement of tolerance to drought imposed at different growth stages of pearl millet, clusterbean, moth bean, sesame, wheat and Indian mustard under improved mineral nutrition (Garg *et al.* 1984; Vyas *et al.* 1987; Kathju *et al.* 1990; Vyas *et al.* 1999; Garg *et al.* 2004).

It has been concluded that fertility induced improvement of metabolic efficiency coupled with higher photosynthesis and nitrate reductase activity for efficient N assimilation are the control mechanism for enhanced growth and yield of diverse pearl millet genotypes under limited water conditions (Kathju *et al.* 2001). Similar conclusions were made in Indian mustard where nitrogen-moisture interaction was explored under stored soil moisture conditions on leaf metabolism, enzyme activities and yield behaviour (Vyas *et al.* 1995; Garg *et al*. 2001).

Likewise alleviation of drought effects in arid legumes (clusterbean, moth bean and mung bean) has been achieved through adequate P fertilization. Phosphorus nutrition is very critical for root growth and functioning, which alters the relations between leaf turgor and stomatal conductance in a number of crops under water stress (Radin 1984; Radin and Eidenbock 1984; Singh *et al.* 1997). Evidence in literature suggests that drought tolerance of cotton, wheat, soybean, white clover, clusterbean, tea and onions was enhanced by improved P supply due to positive interaction between P nutrition and water on root growth, leaf area

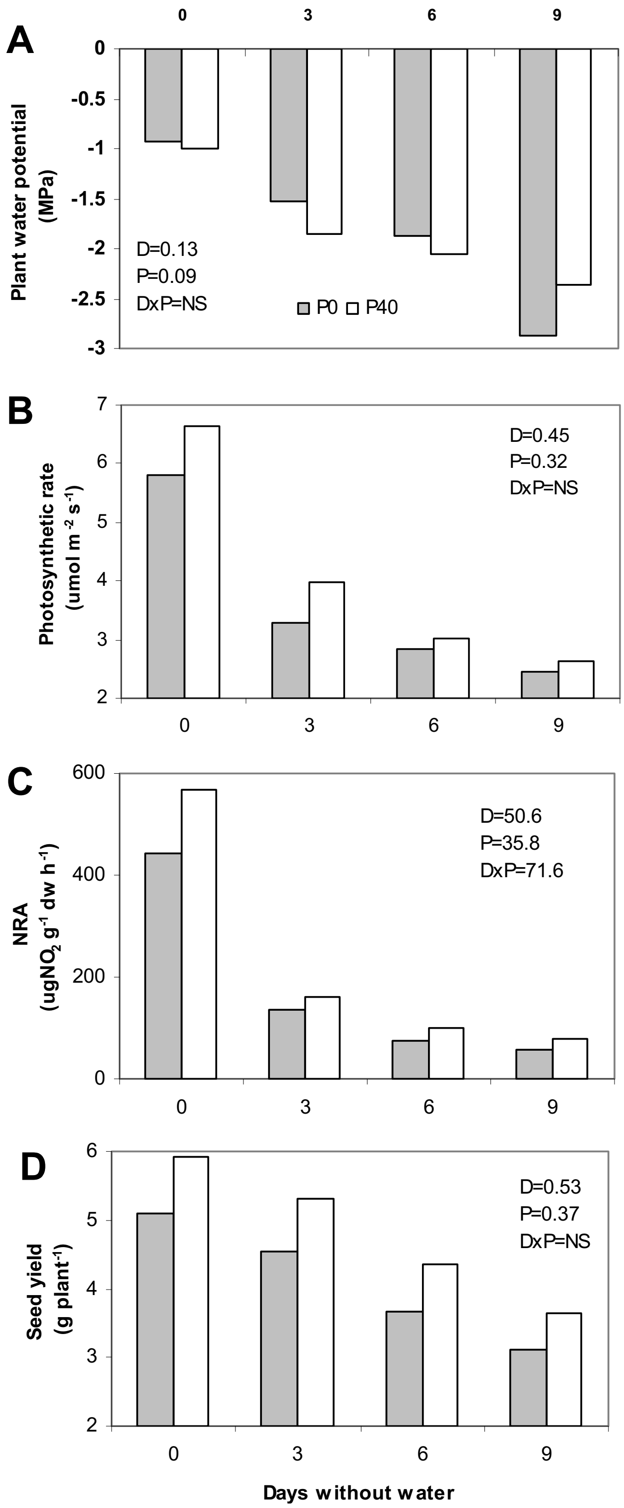

Fig. 6 Influence of P nutrition on plant water potential (**A**), net photosynthetic rate (**B**), nitrate reductase activity (**C**) and seed yield (**D**) of clusterbean under different intensities of water stress. Figure drawn from data in Burman *et al*. (2009).

development, leaf metabolism, photosynthesis and enzyme activities. Our studies with clusterbean (Burman *et al.* 2009) also showed that P nutrition mellowed adverse effects of water stress on leaf metabolites, NR activity and photosynthesis leading to improved seed yields (**Fig. 6**). The magnitude of physiological and biochemical changes induced by P nutrition alone or in combination with N may vary depending on the soil moisture conditions of arid regions. Thus the potential gains may be variable but the merit of P nutrition in yield enhancement through improved metabolic efficiency is quite obvious.

Potassium also plays a critical role under moisture

Table 7 Effect of different levels of potassium (K) on relative water content, photosynthesis, diffusive resistance and nitrate reductase activity of clusterbean under drought (D) at the flowering stage. Data modified from Vyas *et al*. (2001)

Treatments	Relative water content (%)	Photosynthetic rate (μ mol $m^{-2} s^{-1}$)	Diffusive resistance (s cm^{-1})	Nitrate reductase activity (μg NO_2 g^{-1} dwh^{-1})
K levels (ppm)				
25	62.6	5.4	7.16	136
50	66.9	7.4	6.60	189
100	70.8	9.3	5.41	263
200	70.6	11.3	3.90	324
LSD (0.05)	4.2	1.5	1.64	31
Stress level				
Control (C)	87.8	12.6	0.61	365
Drought (D)	47.6	4.2	10.92	91
LSD (0.05)	3.0	1.1	1.16	22

stress conditions through its influence on maintenance of turgor potential, larger root growth and efficient stomatal movements (Lindhauer 1983; Hsiao and Lauchli 1986). K is also involved in maintenance of many physiological processes such as photosynthesis, translocation of photosynthates, starch synthesis and activation of number of enzymes (Mengel and Kirkby 1980) that are adversely affected under drought. Experimental evidence from different crops indicates beneficial effects of K application under soil moisture deficits (Lahiri and Kackar 1985; Singh *et al.* 1997; Vyas *et al.* 2001). Lahiri (1980) and Vyas *et al.* (2001) found increase in seed yield of arid legumes with increasing K levels even under low levels of soil moisture availability. The detrimental effects of water stress imposed at various developmental stages on seed yield of clusterbean were markedly less at higher K levels due to maintenance of favourable plant water status, higher photosynthesis and nitrate reductase activity despite water stress (**Table 7**). Thus maintenance of adequate K supply through fertilizer application, particularly in K deficient soils, is very critical for yield improvement of arid zone crops.

In recent years, the continuous application of only N and P led to the deficiency of micronutrients in the arid soils. Deficiency of micronutrients has great detrimental effects on metabolic pathways, enzyme activities and thereby on the performance of crops and uptake of macronutrients. Their application greatly improved many plant processes e.g. zinc application which increased the concentration and total N uptake in pearl millet (Aggarwal and Singh 1978). Application of Mo (0.2%) increased N content of grains besides increasing nodules and dry weight of pods in clusterbean (Ghosinkar and Saxena 1973). Zn application significantly increased the nitrogenase activity, carbohydrate and protein content in clusterbean (Nandwal *et al.* 1990). Clearly studies are lacking on soil moisture and micronutrients interaction, particularly on arid zone crops, to have a better understanding of the mechanisms involved for growth and yield enhancement under water limited conditions.

SYNTHESIS AND CONCLUSIONS

Droughts in India occur more frequently in arid and semi-arid regions. Western Rajasthan alone carries the onus of nearly 61% of hot arid lands in India. The mean annual rainfall varies from <100 to 450 mm and longest crop growth period available is <6 to 12 weeks only. In this region, biotic pressure is high while resource base both in terms of soil and rainfall is poor. Poor fertility further aggravates the situation. Efforts have been made in this article to discuss the management of nutrients for enhancing the production and productivity of arid zone crops.

Decreasing water availability under drought generally results in reduced total nutrient uptake and frequently in reduced concentration of mineral nutrients in crop plants. The most important effect of water deficits is on transport of nutrients to the roots, on root growth and extension. Reduced absorption of the inorganic nutrients can result from interference of uptake and unloading mechanism besides reduced transpiration flow. One of the earliest signs of drought stress is in the translocation of P from older leaves to the stems and meristematic tissues. Translocation of N closely follows that of P, suggesting the occurrence of protein hydrolysis and alteration of normal cell function. Water stress can also interfere with nutrient distribution in seeds affecting the quality adversely.

In dry land agriculture the basic problem in plant nutrition is that of balancing fertilizer application with the soil moisture status under rainfed on limited irrigated conditions. On the one hand there is a need to limit nutrient application to rates which will not promote more growth than the available moisture can sustain till harvest and on the other hand the aim is to ensure a level of nutrient supply that will enable the plant to use the favourable soil moisture conditions completely and efficiently. Therefore, the interaction between soil moisture and nutrient supply is of critical importance and hence subject of numerous research efforts. This assumes importance because turgor alone may not be responsible for some of the observed decrease in growth and development in stressed plants that may in fact be due to nutrient deficiency.

Our investigations on selected arid zone crops viz., pearl millet, sesame, clusterbean, moth bean and mung bean during rainy season and wheat and mustard during winter have established significant positive responses of plants to improved soil fertility, particularly of nitrogen and phosphorus. On the basis of substantial experimental data obtained on sandy soils, it has been found that advantages of fertilizer application under arid conditions may be realized in situations in which dry and wet phase exist during the growing period. It has been consistently observed that application of fertilizer in nutrient-deficient arid soils increase the crop growth, yield and water use efficiency. However, the benefits of nutrients under such drought conditions were obviously less than in well irrigated crops. Nevertheless, the moderate fertilizer doses seem essential to boost up the crop production in these regions. Furthermore, the improved cultivars have yield superiority and are generally more responsive to the added nutrients to the soil.

The physiological mechanism of drought-fertility interaction has been thoroughly studied in various arid zone crops through a series of experiments under rainfed conditions or simulated water stress conditions. Likewise studies have been conducted on wheat and Indian mustard under limited irrigated conditions during the winter. The favourable and significant responses of nutrient supply on nutrient uptake, biochemical processes, photosynthetic rate, enzyme activities related to N and P metabolism and overall metabolic efficiency have been invariably found in all crops. These beneficial effects have been ultimately reflected in yield enhancement of crops, notwithstanding adverse water stress environments and their detrimental effect on plant processes (**Fig. 7**). It has been well documented that significant improvements in yields of arid zone crops can be obtained even under low soil moisture conditions, through adequate plant nutrition and proper nutrient management. However, it is necessary to consider the economics of fertilizer induced productivity under low and high levels of moisture as this shall help to ascertain as to whether available water be utilized for intensive agriculture in smaller area or else be diverted over large areas for sustenance cropping.

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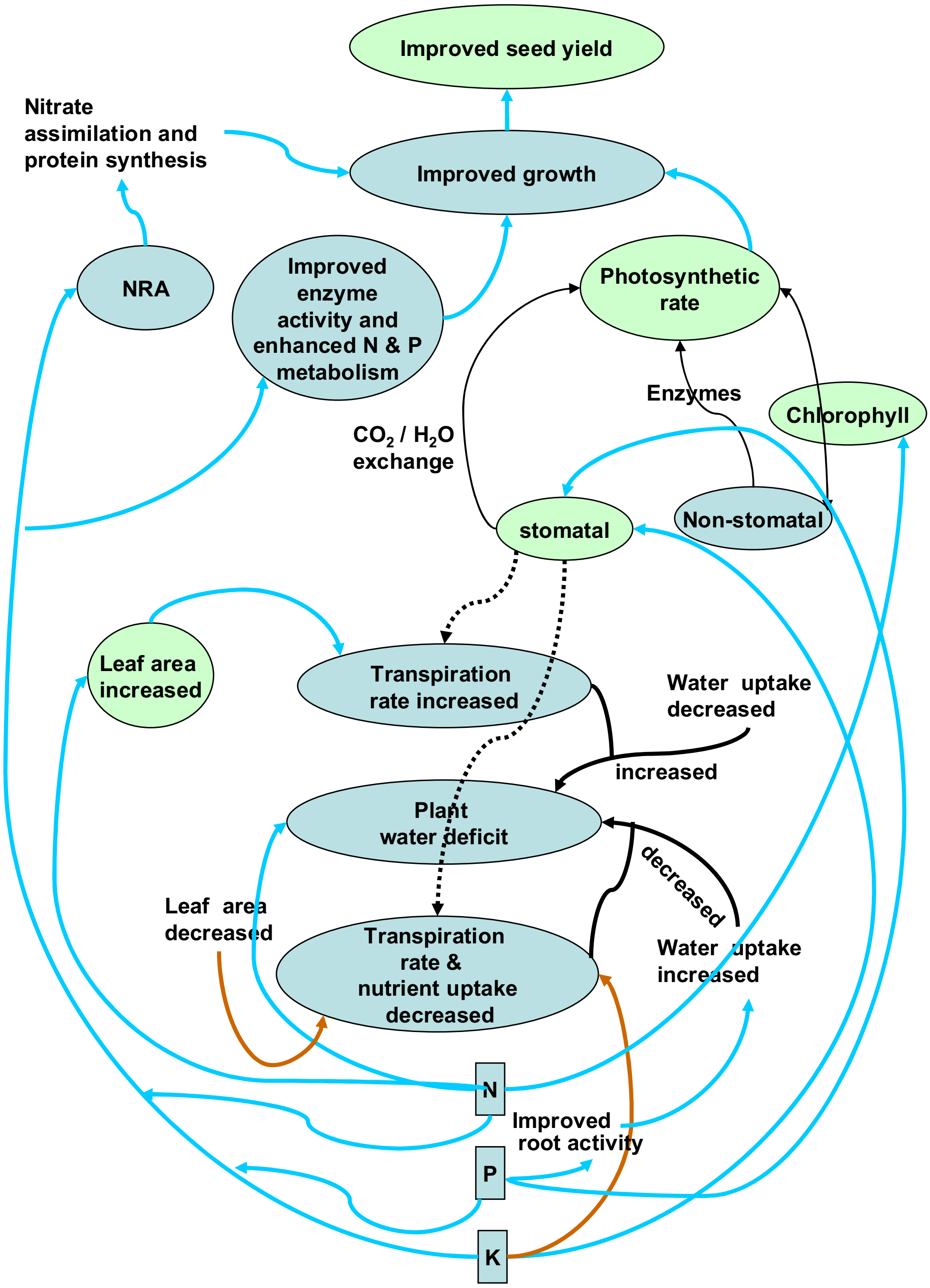

Fig. 7 Diagrammatic representation of diverse physiological, metabolic and growth responses of arid zone crops to application of nutrients (NPK) under water deficit conditions.

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