CHAPTER SEVEN

NUTRIENT AND WATER MANAGEMENT
EFFECTS ON CROP PRODUCTION, AND
NUTRIENT AND WATER USE EFFICIENCY
IN DRYLAND AREAS OF CHINA

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Abstract

Located in the northern territory of China, the vast semiarid and subhumid regions referred to as dryland areas are stressed by two major constraints for crop production: shortage of water supply and deficiency of nutrients in soil. Low precipitation and its uneven distribution have resulted in soil water, surface water and groundwater deficit, and made crops being under water stress in most cases. As a direct result, except for a few places that can conduct irrigation, most regions remain rainfed agriculture. In addition to shortage of water supply, serious wind and water erosion derived from sparse vegetation coverage, windy climate and frequent rainstorms plus human activities have led to serious soil degradation and nutrient stress. Deficiency of N can be found everywhere and that of P occurs at least in one third of the arable lands, this leading to low productivity. However, the limited water resources have not been fully used and the nutrient use efficiency by crops is very low, both having a certain potential for use and a large room for improvement. Management of water and nutrients are extremely important not only for crop production, but for environmental concern in these areas.

Water and nutrients have great interactions that may gain either positive or negative effects on crop production, depending on crop growth stages, amounts, combinations and balance. In the dryland areas, the effect of nutrients and that of water are often limited to each other. Remarkable variations in precipitation from year to year significantly influence soil water and nutrient status, and so do the nutrient input effect. Nutrient input may obtain a good harvest in one year while a poor harvest in another. Considering the precipitation changes and taking effective measures to regulate nutrient supply, crops may not suffer from water limitation in a dry year and from nutrient deficiency in a wet year, and in this way we cannot lose the opportunity to obtain good harvest in both dry and wet year.

Nutrient input is the key for crop production. Roots are essential for taking up water and nutrients to support crop growth, and the significance of roots becomes even more important on drylands, since the topsoil is often dry and nutrients are often unavailable, and plants need to extend their roots into deep layer to obtain available nutrients in the moist soil. It has been found that in most cases, crop yield is highly correlated with crop root mass almost in a linear shape. Addition of organic fertilizers can enhance soil organic matter, raise soil water storage capacity, reduce soil bulk density, and therefore create good conditions for root penetration into deep layer. Both organic and chemical fertilizer can provide nutrients for forming strong root system and for roots having a higher capacity to absorb nutrients and water, improve root activities such as raising the root synthetic ability of amino acids by rational N fertilization. Different nutrients have different functions on root growth and its distribution. Nutrient input is also essential for improvement of plant physiological activities. Regulating plant water status and osmotic pressure, increasing the activity of nitrate reductase in plant leaves and raising photosynthesis and transpiration intensity whereas decreasing evaporation constitute some important aspects. All these benefit plants in
optimization of the use efficiency of water and nutrients. Experimental results show that the osmotic regulation effect is higher with fertilization. The increase of N-supply level reduces disorder of N metabolism in plants deficient in water and increases plant resistance to drought. Under water stress, rational N supply could make wheat leaves to have high activity of nitrate reductase, high levels of proteins, and better water status. Bleeding sap amount increase per plant by N fertilization provides evidence that water intake by plants is increased. Addition of K can make leaf stomata quickly closed under dry and hot wind conditions. With normal water supply, transpiration rate is increased by fertilization while reduced in a water deficit case. Due to vigorous growth, rapid leaf emergency, large leaf area and high coverage rate of plants on the ground with fertilization, soil surface evaporation is reduced and more water is used by transpiration. It has been found that by rational N fertilization, the ratio of water lost by transpiration to that by evapotranspiration was increased from 0.32 to 0.65, and water loss by evaporation was decreased by 1/3, the water use efficiency (WUE) for both grain and dry matter production being increased. Addition of nutrients, particularly K, can increase chlorophyll, protect the photosynthetic organs from dryness and make the photosynthetic organs fully played their role, and therefore increase the photosynthesis that is regarded as the main cause for crop yield reduction under dry conditions. All these have made the dryland crop production increased. Wise input of fertilizer and manure may do more to prevent soil erosion than some of the more obvious mechanical means of control, since the growing of bumper crops by fertilization not only gives a maximum ground cover but supplies sufficient organic matter to aid in the maintenance of all important soil constituents; and the increase of soil permeability to water under such conditions is certainly a factor of major importance.

Effective water management can increase nutrient availability, transformation of nutrients in soil or from fertilizers. Mineralization of organic N is proportional to soil water, and the net mineralized nitrate-N is increased with the increase of water content in an adequate range under suitable temperature. A very closely linear relationship has been found between water content and mineralized N. Due mainly to good aeration induced by deficit of water on drylands, ammonium-N both from soil and fertilizers can be quickly nitrified into nitrate-N. Thus, a large amount of nitrate-N often accumulates in soil profile that has been used as a good index for reflecting soil N-supplying capacity. Adequate water content can promote nitrification of ammonium N while the process is inhibited when moisture content is too high or too low. Water influences mineral nutrient movement from soil to roots and then from roots to aboveground parts of plants. The difference of nitrate N concentrations at different distance points of soil from a plant being greatly declined by adequate irrigation is a typical example showing that some nutrients could be transferred as solute to plant roots with water movement. Adequate soil water content can significantly transfer a large portion of N to aboveground part, and increase N contents in seeds.
All in all, water promotes total nutrient uptake by plants and nutrient use efficiency, and affects nutrient composition of plants. It has been reported that N recovery was increased about 20% at any N rate by an adequate supply of water. Water deficit, on the other hand, not only causes water stress to plants, inhibits plant root growth, reduces roots-absorbing area and capacity, increases the viscosity of sap in hadromestome, and thereby decreases nutrient transfer, but also reduces the availability of soil nutrients, nutrient movement in soil, and nutrient uptake and efficiency. Plant growth and crop yield are thus reduced. However, the reduction rate of plant growth is more serious than nutrient uptake, leading to a relative increase in nutrient concentration. Too much supply of water may cause nitrate N leaching and decrease N recovery. Since water supply and nutrient efficiency are closely related, balanced application of nutrients, and determination of their types, ratios, amounts, timing and methods should be based not only on the nutrient-supplying capacity, but also on water status of soil.

Rational combinative supply of water and nutrients can increase efficiency of both and produce good interaction. When available water supply is less than a certain range, crops may have little response to fertilizers at any rate, and with sufficient supply of water, nutrient efficiency is increased. An intense interaction exists between available water and fertilizer, and one being changed will likewise lead to the change of the other. The interaction of water and fertilizer is time dependant, and application of water and fertilizer at different stages of plant growth may produce different interaction effects. Oversupply of either or both may delay crop maturation by encouraging excessive vegetative growth, while deficit of water may result in high nutrient concentration in soil, making it difficult for crops to take up and use both water and nutrients, and in a worst case, plants may die resulting in “haying off” effect. The different results obtained for the optimal time of application of water and fertilizer may relate to soil water and nutrient supply at different time. For promotion of water and nutrient fully playing their role and realization of maximum yield, high quality and high efficiency, while protection of the environment from fertilizer ill impact, one important thing is to fully understand and utilize their positive interaction, and attention should be paid not only to input of water and nutrients, but to their rational combination. That is, for addition of water, one should consider nutrient supply, and for addition of nutrients, one should consider water coordination, so that limited nutrient and water can produce optimum effect.

Short supply of fresh water and fertilizer pollution has promoted investigations into the interaction effects of water and nutrients on crop yield and nutrient efficiency and WUE, and some achievements have been made. However, there still exist a large number of issues that need further studies in the future. Delineating drylands into different regions and determining the priority issue in each region, determination of most efficient time or growth stage for input of nutrients and water to different crops, and interaction mechanism of water and nutrients are some important aspects.
1. INTRODUCTION

The vast regions of northern territory of China located in arid, semiarid, and subhumid areas are prone to drought (Li and Xiao, 1992; Working Committee of Natural Regionalization, 1959). These areas are referred to as drylands. In these areas, low precipitation per event results in low infiltration and high evaporation loss from surface, and consequently, soil water, surface water, and groundwater are all in deficit. Only a few places conduct irrigation and most regions remain rainfed agriculture. Shortage of water supply is the major constraint to obtain high crop yields. The scarce vegetation coverage induced directly by the sparse precipitation plus windy climate causes severe wind erosion. The impact of sparse precipitation is further intensified by its uneven distribution. Precipitation is mostly concentrated in 3 months (July, August, and September) and only partly meets the water requirements of the crops that grow in the rainy season. Because of this, most crops are under water stress, and this, in turn, increases the threat of water shortage for agricultural production. In addition, frequent storms during the rainy period often lead to serious runoff and water erosion on sloping lands, resulting in serious soil degradation and nutrient losses. Therefore, two serious constraints for crop production in dryland areas are shortage supply of water and nutrient deficiency by soil degradation derived from severe wind and water erosion. The two characteristics are common in dryland regions not only in China, but also in the world (Stewart, 1988).

Like water, lack of nutrients for optimum crop growth is widespread. For example, deficiency of N could be found everywhere (Li et al., 1976a,b,c; Liang et al., 1987; Wu, 1989), and that of P occurs at least in one third of the agricultural lands (Jin, 1989; Li et al., 1978, 1979, 1987; Shao and Zhen, 1989). Because deficiency of nutrients exerts a detrimental impact on plant growth (Arnon, 1975), fertilization produces remarkable results in most cases (Li and Zhao, 1990; Li et al., 1987, 1990a,b, 1991, 1992; Lü and Li, 1987; Lü et al., 1989; Ma, 1987; Yao and Yang, 1989; Zhang, 1984). Nutrient input promotes root growth, makes roots absorb more water from deep soil layers (Shan, 1983a,b), and therefore increases plant tolerance ability to drought, all being beneficial for crop production (Cao, 1987; Chen et al., 1989; Hu et al., 1989). However, crop nutrient use efficiency is extremely low. In China, the average recovery of P fertilizer in a two-crops-per-year system ranges from 10% to 15% for the first crop that receives the fertilizer, and only about 25% for two crops. The N fertilizer recovery varies from 28% to 41% for crops receiving the fertilizer, and the residual effect is negligible in some cases. The insufficient use of fertilizers becomes even more serious on drylands due to water supply limitation. The poor nutrient use efficiency has not only led to
low economic returns, but also has detrimental impact on the environment, such as nitrate pollution of groundwater (Ma, 1992), nitrate accumulation in vegetables (Wang and Li, 1996), nutrient enrichment of surface water (Ma, 1992), and emission of greenhouse gas as N₂O (Bowman, 1989).

Although each of water and nutrients has its own function, they are related and interact with each other (Brown, 1972). One can supplement or constrain the other by controlling, restricting, or checking function in plant. Their interaction may gain either positive or negative effects on crop production, depending on crop growth stages, amounts, combinations and balance. Only in the case of rational input of nutrients and water, based on water status to supply nutrients, can the synergic and supplementary effect be achieved, making both playing a much higher role than their sequential additive effect. This is their positive interaction, a bonus by adding to outcome but not in costs.

Since both nutrients and water are deficient in dryland areas, the effect of nutrients and that of water is often limited to each other (Cheng et al., 1996). Due to scarce precipitation and drought occurrence, nutrient input under different dryland conditions has different results, depending on the degree of water deficit and timing of fertilization. It has been found that with the increase of available P in soil, plants took up more P in a wide range of soil water contents. However, fertilization causes overconsumption of water by producing abundant vegetative growth at early stages, and can lead to a significant reduction in seed yield (Wang et al., 2004). Under lower soil water content, nutrient availability and its use efficiency are all decreased. Nutrient input may obtain a good harvest in one year, but a poor harvest in another (Eck and Stewart, 1954). Previous research on the effect of fertilization on millets (Pennisetum typhoides L.) in 4 successive years at Jodhpur, India, found that under an extremely dry condition, fertilization had no effect, while under a sporadic drought condition, fertilization was certainly beneficial to crop growth and seed yield (Du et al., 1995). Russell (1979) reported that fertilization was of little significance when precipitation was less than 120 mm during spring wheat-growing period. Dai and Yang (1995) revealed a negative effect of N and P fertilization on winter wheat with precipitation less than 109 mm during the crop-growing period. Precipitation varies from year to year, so does the fertilizer effect. In an extremely dry year, the more fertilizer is applied, the more serious is the reduction in crop yield (Chen et al., 1992). Since remarkable variations in precipitation on drylands significantly influence soil water and nutrient status, considering the precipitation changes and taking effective measures to regulate nutrient supply, crops may not suffer from water limitation in a dry year and from nutrient deficiency in a wet year, so that we cannot lose the opportunity to obtain good harvest in both dry and wet year. The purpose of this review paper is to summarize research information related to nutrient and water management on root growth, plant physiological
activities, soil water storage, crop yield, nutrient and water use efficiency (WUE), effect of water on nutrient behaviors, and water and nutrient interaction on crop yield in dryland areas of China, and most of important results are obtained from our research group.

2. **Effects of Nutrient Input on Root Growth, Plant Physiology, Soil Water Storage, Water Use Efficiency, and Crop Yield**

2.1. Root growth

Roots are a major part of a plant and play a very important role in plant growth. In addition to fixing and supporting plants, the main function of roots is to absorb water and nutrients. Li *et al.* (1978, 1979, 1994) showed that rational input of N together with P fertilizer increased wheat root growth and yield, the yield increase being highly correlated with crop root mass in a linear shape. Although water and nutrients can move from one point to another, the function of roots cannot be replaced by their movement.

Significance of roots becomes even more important on drylands, since the topsoil is often dry and nutrients are often unavailable, while the deep soil is usually moist with some available nutrients. Consequently, plants may depend more on deep soil layers for water and nutrient supply than topsoil. For surviving in such a condition, plants extend their roots into deep layers and form large root branches and root surface areas, which may be responsible for some crops that have a certain drought resistance. Smith (1954) demonstrated that in dry areas, fertilization extended roots quickly into deep soil layers to take up water stored during the summer-fallowing period. Brown (1972) found that water absorbed by wheat was limited to 91-cm depth without fertilization, while doubling the water intake soil depth and increasing its use efficiency by 56% with N application.

The magnitude of fertilization role is closely related with soil fertility. In a soil poor in plant nutrients, rational addition of either organic or inorganic fertilizer can make root growth stronger and have a higher capacity to penetrate through the compact, hardpan layer to absorb nutrients and water from the subsoil (Marschner, 1986). Taylor and Gardner (1963) claimed that a soil with high compaction caused by high bulk density, high cohesion and firmly combined clods could seriously change the normal growth patterns of roots, and reduce the elongation rate of either main roots or their branches. This could be changed by application of organic manure. Jamison (1953) concluded that increasing organic manure rate to a fertile soil was not as effective as to an infertile sandy soil.

Different nutrients have different functions on root growth and its distribution (Anghinoni and Barber, 1980). When roots penetrate into...
areas of the soil containing abundant mineral elements, they branch pro-
fusely (Weaver and Clements, 1938). The addition of commercial fertilizers
to the upper few centimeters of soil layer undoubtedly favors the concen-
tration of crop roots near the surface. Not so much is known about the
specific effects of various nutrient elements on roots as on shoots, but it is
recognized that P stimulates root growth, and deficiencies of boron and
calcium produce short, stubby branches, while the root tips often die
(Kramer, 1983). In general, an abundance of essential mineral elements,
particularly N, stimulates root growth, but shoot growth is increased even
more, so the ratio of shoot to root is usually higher in fertile than in infertile
soil. Subsoiling caused little increase in depth of rooting, but fertilizer
addition to the subsoil caused deep rooting (Bushnell, 1941). Placement
of P stimulated maize root growth in the fertilized portion of the soil,
while N, particularly nitrate, which moves readily in the soil, influenced
root distribution (Claassen and Barber, 1977).

Nutrient supply also influences root distribution. Li et al. (1982) found
that on average wheat root length was only 1.45 m with N addition, almost
equal to that without fertilization (1.4 m), while P application increased
root length to 2.7 m. Water content in the 140–200 cm layer was 17% for
plots with or without N application, but almost no water was left in the
200-cm layer with P fertilizer. In north Syria, Gregory (1988) found that
application of P fertilizer alone only increased root growth in the surface
soil, but application of P and N fertilizers together extended the root
distribution to the entire soil profile where plant roots could penetrate.
Combined application of N and P fertilizers increased root length in both
surface and deep soil layers (Brown et al., 1987).

Nutrient input rates and timing affect root-growing time, distribution
space, and activities. Comfort et al. (1988) demonstrated that high N rate
inhibited wheat root extension into deep soil layer, and reduced water and
N utilization from that soil. Zhao and Huang (1993) concluded that high N
rate increased aboveground biomass of plants, but reduced their root bio-
mass. Liu (1992) and Liu and Shi (1993) found that dressing an adequate
amount of N increased root mass, secondary root number, and root activ-
ities, but it was not so when N rate reached to a higher level. Controversy
reviews also exist, the argument being in that due to extensive root growth,
the soil water is quickly exhausted, and this can cause death of roots in the
water-depleting zone (Taylor and Hlepper, 1973).

2.2. Plant physiological activities

A rational nutrient input can improve plant physiological activities in
various manners. Li et al. (1994) found that in addition to NO$_3^-$ – N and
NH$_4^+$ – N, the bleeding sap contained remarkable amino acids that
increased with increasing N rate (Table 1). Although amino acids exist in
soil (Wen, 1992), the amount is little, and cannot be increased with N rate increase. This shows that the amino acids were synthesized in plant roots, and N fertilization raised root synthetic ability.

Nutrient input affects plant water status and its tolerance to drought. Some reports showed that under dry soil conditions, application of organic or inorganic fertilizer increased plant water potential (Xu, 1985), made plants maintain higher water content in tissue, increased the proportion of free water to bound water, and therefore improved plant water status (Cao et al., 2002; Zhang and Li, 2005). However, other results showed that fertilization decreased leaf water potential (Shan, 1983a,b; Xu and Shan, 1991; Yanbao and O’Toole, 1984). The relative leaf water contents may be decreased or increased (Xie and Chen, 1990), and the proportion of free water to bound water is not changed by fertilization (Zhang and Shan, 1995). Li et al. (1994) revealed that the crop growth was much better and leaf water content was higher with N fertilization, but the leaf water potential was decreased with N rate increase due to the high solute concentration in leaves. Zhao et al. (1991) suggested that plant leaf water potential (PLWP) was mainly related to atmospheric water potential in addition to soil water content. When soil and atmospheric water potentials were lower, fertilization decreased PLWP, while increasing it when both higher. In contrast, when soil water potential was higher and atmospheric water potential lower, atmospheric water potential was the major factor affecting PLWP (Mei and Tao, 1993).

Osmotic regulation is an adaptive mechanism of plants under water stress. The rise of cell solutes leading to decline of osmotic pressure is beneficial to maintain turgor pressure and its relevant cell elongation, stoma opening, and photosynthesis (Shan, 1985; Xu and Shan, 1988). A high capacity to regulate the osmotic pressure was found in leaves of

<table>
<thead>
<tr>
<th>N form</th>
<th>Tillage system</th>
<th>Rate of N (kg N ha(^{-1}))</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>NO(_3^−) – N</td>
<td>Conventional</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>Plastic mulching</td>
<td>0.90</td>
</tr>
<tr>
<td>NH(_4^+) – N</td>
<td>Conventional</td>
<td>0.96</td>
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<tr>
<td></td>
<td>Plastic mulching</td>
<td>1.96</td>
</tr>
<tr>
<td>A.A.–N</td>
<td>Conventional</td>
<td>1.24</td>
</tr>
<tr>
<td></td>
<td>Plastic mulching</td>
<td>1.63</td>
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</tbody>
</table>

Table 1 Effect of rate of applied N to soil on ammonium–N (NH\(_4^+\) – N), nitrate–N (NO\(_3^−\) – N), and amino acid–N (A.A.–N) content (mg N plant\(^{-1}\) d\(^{-1}\)) in bleeding sap of plant

Modified from Li et al. (1994).
rice seedlings cultured at high N solution (Yanbao and O’toole, 1984) and in wheat with N fertilization (Xie and Chen, 1990). However, Radin and Parker (1979) argued that there was no such relation between N nutrition and osmotic pressure regulation. Morgan (1986) reported that during the process of PLWP declining, the leaf osmotic potential of wheat was lower with low N rate than with high N rate, thus maintaining higher turgor pressure. Phosphorus did not affect cotton leaf osmotic regulation (Ackerson, 1985), while K supply increased wheat osmotic regulation under dry conditions, but no effect with normal water supply (Chen, 1993). With soil water content varying from 40% to 70% of the maximum capillary water-holding capacity (WHC), N, P, and K fertilization had almost no effect on osmotic regulation; when soil water content declined to 20–30%, the osmotic regulation effect was higher with fertilization (Xu and Shan, 1988).

Zhang and Wang (1988a,b) found that increasing N supply level reduced disorder of N metabolism in plants deficient in water and increased plant resistance to drought. Also, under water stress, rational N supply could make wheat leaves to have high activity of nitrate reductase, high levels of proteins and RNA, and better water status.

Regulation of transpiration intensity reflects another function of fertilization in improving plant physiological activities (Du et al., 1995). Transpiration has both negative and positive impact on plant growth. Water loss from plants is the major negative impact and water uptake increase is the other. Without transpiration, the process of water absorption by transpiration-pulling force would not be performed. Transpiring more water is able to reduce the possibility of water loss by evaporation. Experiments from Li et al. (1994) showed that under a moderate water supply, input of N fertilizer significantly increased transpiration intensity (Table 2; Fig. 1).

Since nutrient input improves the capacity of crop to absorb and transfer water and nutrients from soil, water intake by plants is significantly increased. This can be seen clearly from plant bleeding sap amounts (Du et al., 1995; Li et al., 1994). Compared to no fertilization, roots in fertilized plots were not only stronger, but also had higher capacities to take up water and nutrients. With either mulching or conventional tillage, the amount of bleeding sap, although no difference at the early stage of maize growth, was increased with N rate increase at vigorously growing stages (Table 3).

Stomata of N-deficient plants could not so freely open and close as those with sufficient N supply (Shimshi, 1970). Deficient in water and N, fescue grass (Festuca Linn.) increased stoma resistance and made leaves rolled up seriously. With a normal irrigation, WUE was higher with sufficient N supply, but under a dry condition, WUE was increased more by low rate of N supply (Ghashagaie and Saugier, 1989). Potassium also plays a great role in regulating stoma resistance. The function of K in regulation of stomata is regarded as the major mechanism in controlling water status of
higher plants; for K-deficient plants, stoma opening was seriously affected (Marschner, 1986). Skogley (1976) found that under dry and hot wind conditions, supplied with favorable K, barley leaves closed their stomata in 5 min while 45 min were needed for those deficient in K.

Wheat experiments showed that under a normal supply of water or under a moderate soil dryness, leaf stoma resistance was significantly lower

Table 2  Effect of rate of applied N to soil on transpiration intensity of maize (g plant\(^{-1}\) h\(^{-1}\)) under mulching and conventional tillage

<table>
<thead>
<tr>
<th>Tillage system</th>
<th>Rate of N (kg N ha(^{-1}))</th>
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<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Conventional</td>
<td>18.1</td>
</tr>
<tr>
<td>Plastic film mulching</td>
<td>13.7</td>
</tr>
</tbody>
</table>

Modified from Li et al. (1994).

Figure 1  Effect of N fertilizer application on transpiration intensity of maize. Drawn with data from S. X. Li (unpublished results).

Table 3  Effect of rate of applied N to soil on bleeding sap content (g plant\(^{-1}\) d\(^{-1}\)) determined at vigorously growing stage of maize

<table>
<thead>
<tr>
<th>Tillage system</th>
<th>Rate of N (kg N ha(^{-1}))</th>
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<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Conventional</td>
<td>0.90</td>
</tr>
<tr>
<td>Plastic sheet mulching</td>
<td>0.97</td>
</tr>
</tbody>
</table>

Modified from Li et al. (1994).
for plants with fertilization than those with no fertilization, the latter significantly reducing water loss per unit area of leaves by transpiration (Zhang and Shan, 1995). At the late growth stages of spring wheat, under a serious soil dryness or normal water supply, WUE by a single leaf was raised by 20–40% compared to that without fertilization. Zhao et al. (1991) concluded that when both soil and atmospheric water potentials were lower, fertilization increased the stoma resistance but decreased the transpiration intensity. The effect of fertilization on transpiration was different under different water supply conditions: with normal water supply, transpiration increased by fertilization; in a water deficit case, fertilization reduced the transpiration rate. Due to vigorous growth, rapid leaf emergency, large leaf area, and high coverage rate of plants on the ground with fertilization (Muchow, 1988; Shangguan and Chen, 1990), soil surface evaporation was reduced and more water was used by transpiration.

2.3. Photosynthesis

Water stress resulting in weakness of photosynthesis may be the main cause for crop yield reduction under dry conditions (Guo et al., 2004; Wang et al., 1992; Xie et al., 1992). However, there are different views on what causes the photosynthetic weakness. Some investigators (Baker and Musgrave, 1964) indicated that decline of stoma conductivity was the cause, but others showed that it was due to the influence of water stress on mesophyll cell or on photosynthetic activity of green chloroplast (Boyer, 1976). Xu and Shan (1992) and Zhang and Shan (1995) demonstrated that the net rate of photosynthesis was not all determined by stoma resistance. When soil was extremely dry, the net rate of photosynthesis of fertilized spring wheat was decreased to a large extent, but the absolute amount was still higher than that not fertilized. Such a good effect of high N rate on reduction of the injury by dry stress might be related with the high activity of mesophyll cell (Xie and Chen, 1990). Li (1993) demonstrated the effects of K addition to maize on increasing chlorophyll, postponing the injured time and magnitude of photosynthetic organs suffered from dryness, and protecting the photosynthetic organs from dryness. Pier and Berkowitz (1987) also drew up such conclusions. Yao et al. (1989) confirmed the effects of K application to rice on increasing chloroplast grana, intensifying Hill reaction, raising activity of photosynthetic phosphorylation (photophosphorylation), forming large and numerous mammillas inside of leaves, and significantly increasing the degree of siliconization. As a direct result, leaves grew straighter, the light condition was improved, and the photosynthetic organs fully played their role under a more suitable condition of light. Zhou et al. (1993) have proven that improvement of P nutrition to tobacco resulted in decline of compensation point of carbon dioxide, rise of photosynthetic rate, and reduction of photorespiration.
2.4. Soil water storage

Well related with soil organic matter, water storage capacity is a major nature of soil property linked to crop production. Research has shown that WHC is highly correlated with organic matter content in soil (Jamison, 1953; Unger, 1975). Addition of fertilizers, particularly organic fertilizer can increase soil organic matter, and thereby increases soil water storage capacity. Zhao et al. (1991) found that soil water potential during winter wheat-growing period increased with fertilizer rate increase. The increase occurred both in top and in deep soil layers, and such a trend did not change approximately until maturity. Zhang et al. (1982) reported that by applying 7.5-Mg organic manure ha\(^{-1}\) to a dry, infertile soil, the amount of water stored in 2-m layer was 44.7 mm more than that with no manure application. Cheng et al. (1987) found that application of organic manure increased the amount of stored water by 30 mm within 2-m layer of a manured loessial soil. Ma et al. (1984) claimed that application of organic fertilizer together with mineral fertilizers did not only increase soil nutrients and improve plant nutrition, but also enhanced soil organic carbon. This promoted formation of organic–mineral colloidal complex, improved soil structure and its water-holding capacity, resulting in increased soil fertility, crop yield, and WUE. Li (1982) studied WUE of wheat on drylands and concluded that WUE was increased with soil fertility improvement. The preceding findings have led the authors to suggest that application of fertilizers, especially organic fertilizers/manures, to dryland soil could increase water content and water potential at early growth stages of plants, making part of the ineffective water available to plants, resulting in a mobilizing effect of fertilization on WUE. Yao et al. (1994) also drew up the same conclusion.

2.5. Reduction of water loss by evaporation and increase of water transpiration

Due to rise of water transpiration and reduction of water evaporation, rational nutrient input leads to an effective use of water by plants and thereby increases dryland agricultural production. Li et al. (1995) conducted a field experiment with and without plastic film mulching using maize as a test crop. During plant-growing period of the experiment, water content in the 0–200 cm soil layer and maize biomass were determined every 10 days. The plastic film was lifted away from the land just before rainfall or irrigation for the soil to receive water. For plots with plastic film mulching, the water loss during plant-growing period is only caused by transpiration, while for plots without mulching, both transpiration and evaporation cause water loss. The difference of water loss between mulched and nonmulched plots cannot be regarded as evaporation loss in the case without mulching, since water, nutrients, aeration, and temperature in mulched plots are different from those
of the nonmulched ones. However, all the differences would be reflected in the crop growth status or the biomass that can indicate the leaf area, and thus the function of transpiration. Based on such a consideration, a good-fitting linear regression equation was established for transpiration amount against maize biomass using data obtained from mulched plots (Fig. 2). Using the equation and the biomass data of nonmulched plots, water loss by transpiration in the field was calculated, and that by evaporation was estimated (Table 4). Results showed that with N fertilization, water loss by transpiration was increased, and that by evaporation decreased, and the ratio of transpiration to evapotranspiration significantly increased. Both decrease of evaporation and increase of transpiration were linearly related to N rate increase. The reason is clear: with N fertilization, the crop grew vigorously, and took up more water from soil, reducing water loss by evaporation. On the other hand, larger leaf areas covered the soil surface, lowered its temperature, and therefore reduced water evaporation rate (Fig. 3). Also, rational fertilization made the transpired water more effective, transforming it into photosynthetic products, as evidenced by the higher sugar concentration in crop leaves at different N rates (Li et al., 1994).

2.6. Improving water use efficiency

Rational nutrient input enhances crop intake of total water, especially from deep layer, increases WUE, brings about full utilization of soil water, and thereby decreases the possibility of crop suffering from drought during dry spell. Brown (1972) increased seed yield of winter wheat from 1610 to 3090, and to 3630 kg ha$^{-1}$, while water uptake amount from soil increased from 61 to 112, and to 155 mm by applying 0, 67, and 268 kg N ha$^{-1}$, respectively.

![Figure 2](image_url)  
**Figure 2** Relationship between transpiration amount and shoot biomass. Drawn with data from Li et al. (1994).
Ramig and Phoades (1963) observed that under water stress of more than 15 atmospheric pressures, N-fertilized wheat took up 25–50 mm more water from 2-m soil layer than that without N fertilization. Shan (1985) revealed that maize grown in fertilized fields utilized 60-mm more water (almost equal to one third of the water consumed by the crop from 0- to 300-cm soil layer) than that in an unfertilized field. In Guyuan, Ningxia Hui Autonomous Region, production of 15 kg grain ha\(^{-1}\) consumed 2.99-mm water on fertile lands while consuming 5.5-mm water on unfertile lands. Ma et al. (1984) showed that winter wheat absorbed 21–77 mm more water from 0- to 100-cm soil layer with fertilization than that without fertilization, increasing WUE by 40–120% in a semiarid area. Han et al. (1990) demonstrated that wheat yield following pea reached 4.77 Mg ha\(^{-1}\), and WUE was increased to 15 kg mm\(^{-1}\) ha\(^{-1}\) by fertilization. Cheng et al. (1987) increased wheat yield

### Table 4  Effect of rate of applied N to soil on transpiration, evaporation, and water use efficiency (WUE\(_{ET}\) and WUE\(_{T}\)) of spring maize

<table>
<thead>
<tr>
<th>Determination</th>
<th>Rate of N (kg N ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td><strong>Plastic sheet mulching</strong></td>
<td></td>
</tr>
<tr>
<td>Grain yield (kg ha(^{-1}))</td>
<td>2180</td>
</tr>
<tr>
<td>Dry matter (kg ha(^{-1}))</td>
<td>5715</td>
</tr>
<tr>
<td>Transpiration (mm)</td>
<td>178.3</td>
</tr>
<tr>
<td>WUE(_{T}) for grain</td>
<td>12.3</td>
</tr>
<tr>
<td>WUE(_{T}) for dry matter</td>
<td>32.1</td>
</tr>
<tr>
<td><strong>Without plastic sheet mulching</strong></td>
<td></td>
</tr>
<tr>
<td>Grain yield (kg ha(^{-1}))</td>
<td>1749</td>
</tr>
<tr>
<td>Dry matter (kg ha(^{-1}))</td>
<td>5715</td>
</tr>
<tr>
<td>Total water loss (evapotranspiration) (mm)</td>
<td>330.3</td>
</tr>
<tr>
<td>Transpiration (mm)</td>
<td>106.0</td>
</tr>
<tr>
<td>Evaporation (mm)</td>
<td>224.2</td>
</tr>
<tr>
<td><strong>Water use efficiency</strong></td>
<td></td>
</tr>
<tr>
<td>T/ET</td>
<td>0.32</td>
</tr>
<tr>
<td>WUE(_{ET}) for grain production</td>
<td>5.3</td>
</tr>
<tr>
<td>WUE(_{ET}) for dry matter production</td>
<td>15.0</td>
</tr>
<tr>
<td>WUE(_{T}) for grain production</td>
<td>16.5</td>
</tr>
<tr>
<td>WUE(_{T}) for dry matter production</td>
<td>46.9</td>
</tr>
</tbody>
</table>

Modified from Li et al. (1994).
to 6.6 Mg ha\(^{-1}\) and wheat precipitation use efficiency (WPUE) to 15.6 kg mm\(^{-1}\) ha\(^{-1}\) by applying organic and inorganic fertilizers together while WPUE was less than 10 kg mm\(^{-1}\) ha\(^{-1}\) without fertilization. Li (2008) cited a report that application of 60 kg N and 60 kg P ha\(^{-1}\) increased water uptake amount by 40–70 mm, and WUE by almost 100%. Gao et al. (1995) further demonstrated the great role of nutrient input in improving WUE.

WUE is a term used to describe the relation of plant biomass to water use. Strictly, it is not the “efficiency” because a true efficiency is a comparative term (i.e., dimensionless) requiring a theoretical maximum value. For this reason, some researchers prefer to use other terms such as water use “coefficient” or “ratio.” Further, as Sinclair et al. (1984) pointed out, “WUE has been used interchangeably to refer to observations ranging from gas exchange by individual leaves for a few minutes, to grain yield response to irrigation treatments through an entire season.” Despite some arguments, the term is still adopted by agronomists in China and elsewhere.

The quantity of water used to produce crop yield may be expressed in several ways. Commonly, it is measured as the residual term in water balance equation and expressed as total water use, evaporation directly from the soil surface (E) plus transpiration, or the evapotranspiration (ET) during plant-growing season. It may also be defined as transpiration alone or as the total water input (precipitation only on drylands) to the system in plant-growing season. These can be expressed in the following equations:

\[
W_{\text{ET}} = \frac{Y}{ET},
\]
\[
\text{WUE}_T = \frac{Y}{T},
\]
\[
\text{WUE}_P = \frac{Y}{TP},
\]

where \(Y\) is the crop yield, either total dry matter production or economical products; \(ET\) is the evapotranspiration; \(T\) is the total transpiration; and \(P\) is the total precipitation in the plant-growing season.

The WUE calculated by evapotranspiration (WUE\(_{ET}\)) may be used for evaluating effects of cropping practices on the difference of water loss by both evaporation and transpiration under different crop production systems as well as on the degree of effectiveness of water use. The WUE calculated by transpiration (WUE\(_T\)) may be used for providing information on water metabolism function of a plant and on the relation between plant growth and water use. The WUE calculated by total precipitation (WUE\(_P\)), including water loss in different ways and residual water still existing in soil profile, during plant-growing period, may be of significance for a long-term study in evaluation of effects of cropping measures on the bioavailability of water resources. Based on our experimental results, first two equations have been utilized to provide an overall evaluation of both agricultural measures and plant water metabolism. Results presented in Table 4 showed that there was almost no difference in the consumption of total water between fertilized and nonfertilized plots. However, due to significant increase in crop yield by N fertilization, magnitude and stability of WUE\(_{ET}\) was greatly increased for both grain and dry matter production with N rate increase. The function of fertilization was not due to consumption of more water, but due to increase in crop yield per unit water use (Fig. 4). Results of the WUE\(_T\) more clearly reveal the effects of N fertilization on WUE. Without N fertilization, 1-mm water transpiration produced only 14.3 kg ha\(^{-1}\) of grain and 23.4 kg ha\(^{-1}\) of dry matter; while with N fertilization at appropriate rate, the corresponding average values were increased to 16.8 and 36.5 kg ha\(^{-1}\). The increase in harvest index benefits grain production (Li et al., 1994). Transpiration coefficient is the ratio of water consumed to the product obtained in same weight unit, and this can express WUE in another way. Transpiration coefficient was greatly reduced with N fertilization (Fig. 5).

### 2.7. Soil erosion control

For sustainable agriculture, the most important and at the same time the most underrated means are the maintenance of high soil fertility and productivity. The growing of bumper crops not only gives a maximum ground cover but also supplies sufficient organic matter to aid in the maintenance of all important soil constituents. The increased permeability of soils to water under such conditions is certainly a factor of major importance. Although not usually recognized as erosion-control features, wise input of fertilizer and manure may do more to prevent soil erosion than some of the more obvious
mechanical means of control (Brady, 1974). Zheng et al. (1987) demonstrated that adequate input of nutrients significantly reduced sheet and rill erosion, thus improving soil quality, fertility, and productivity.

3. Effects of Soil Water Supply on Nutrient Utilization

3.1. Nutrient availability

Organic matter and minerals in soil contain nutrient elements. Mineralization of organic matter and weathering of minerals provide available nutrients plants need, and are the basis of natural soil fertility and major sources of

![Figure 4](image4.png)

**Figure 4** Relationship between N rate and water use efficiency of maize. Drawn with data from Li et al. (1994).

![Figure 5](image5.png)

**Figure 5** Relationship between transpiration coefficient of maize and N rate. Drawn with data from Li et al. (1994).
plant nutrients. Fertilizers applied to soil can be changed into either available or unavailable forms. Many factors affect the availability of soil nutrients, and soil water is the most important one.

Water affects original nutrient transformation in soil turning unavailable nutrients into available forms. It also affects the rate of transformation of fertilizers added to the soil. Consequently, it affects absorption of nutrients, total nutrient uptake and nutrient composition of plants. Dry climate or water stress influences the availability of nutrients to crop plants, and thus the total uptake amount. In general, water stress reduces both plant growth and nutrient uptake, but the reduction rate of net assimilation is more serious than nutrients, leading to a relative increase in nutrient concentration. Marschner (1986) pointed out that in any case, water supply changes resulted in corresponding changes in distribution of roots in soil profile and nutrient uptake amounts from different layers. Grimme et al. (1981) demonstrated the differences in nutrient uptake from different soil layers under different water conditions. For example, spring wheat grown in a soil developed on loess parent material took up 50% K on average from deep soil layer at its late growth stages. However, this was changed from year to year with variation in precipitation. In a dry year it was 60%, while in a wet year it was only 30%. Even in topsoil containing highly available P, spring wheat still took up 30–40% of P from deep soil layer under a water-limiting condition. Water status does not only influence the availability of nutrients existing in the topsoil layer, but also in the deep soil layer. This is more obvious for N transformation.

Stanford and Epstein (1974) found relationship between amount of mineralized N in a 2-week period at 35 °C and water content was as follows:

\[ Y = 1.02x - 4, \]

where \( Y \) is the relative amount of N mineralized in term of percentage (mineralized N under optimum water content was set to 100%), and \( x \) is the relative water content (optimum water content for N mineralization was also set to 100%). In the equation, the constant (i.e., intercept) was not large, and the slope was approximated to 1, indicating that relationship was similar to one to one (\( y = x \)). This means that mineralization of organic N was proportionally increased with soil water.

In an aerobic incubation experiment over 147 days at four temperatures (5, 15, 25, and 35 °C), and four soil water levels (8%, 15%, 22%, and 29% by weight of oven-dried soil with maximum WHC of 32%), Ju and Li (1998) showed that net mineralized nitrate–N increased with the increase of water content from 8% to 29% of oven-dried soil weight, the magnitude depending on temperature. This indicated that only under suitable combinations of water and temperature could the soil organic N be well mineralized,
and provided much more nutrients for plant use (Table 5). A very closely linear relationship was found between water content and mineralized N (Table 6; Fig. 6) for both the short-term (2 weeks) and long-term (21 weeks) incubation. For the 2-week incubation, the relation was

\[ Y \approx 3.68 + 1.06x \quad (r = 0.99) \]

and for the 21-week incubation, it was

\[ Y \approx 9.59 + 0.90x \quad (r = 0.99), \]

where \( Y \) is mineralized N in mg N kg\(^{-1}\) soil, and \( x \) is the soil water content (%). The two equations are very similar to that of Stanford and Epstein (1974), and the regression coefficients almost approximate to 1, further showing the one-to-one relationship.

Ammonium and nitrate are two major forms of N that can directly be taken up by plants. Of these, nitrate is more important for supplying N to plants than ammonium in dryland areas. Due to mainly good aeration on lands, ammonium–N from both soil and fertilizers can be quickly transformed into nitrate–N. Thus, a large amount of nitrate–N often accumulates in soil profile while ammonium–N in a small amount. Most of dryland soils are calcareous with high pH, and transformation of ammonium–N into nitrate–N can reduce N volatilization whereas leaching of nitrate–N by scarce rainfall is negligible. It has been proven that nitrate–N content in soil profile is a good index for reflecting soil N-supplying capacity (Hu and Li, 1993a,b,c,d). Water content effectively affects ammonium–N nitrification. In the range of 12–27% of water content in soil, nitrification rate was linearly correlated with the increase in soil water content. Flower and Challagha (1983), Li (1990), and Malhi and McGill (1982) revealed that nitrification reached maximum when soil water content ranged from 50% to 70% of maximum WHC, and it was inhibited when moisture content was higher or lower than this range. In an incubating experiment on nitrification of 3 N fertilizers applied at 0.19 g N kg\(^{-1}\) to soil at 12–27% water contents of a soil with 32% WHC and 26 °C showed that net nitrification of ammonium–N from fertilizers was closely related with soil water content (Tables 7 and 8). In this water range, the higher the water content, the fewer the ammonium–N left and the higher the nitrate–N content occurred in the soil. A close linear relationship was found between rate of nitrification and soil water content (%) for each fertilizer as shown below:

for ammonium bicarbonate

\[ Y \approx 10.07 + 78.13X \quad (r = 0.9733^{**}), \]
Table 5  Effect of temperature and water content on net mineralized N (mg N kg$^{-1}$)\textsuperscript{a} in soil after certain days of incubation

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Soil water content (%)</th>
<th>Days of incubation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>29</td>
<td>6.7</td>
</tr>
<tr>
<td>15</td>
<td>8</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>7.4</td>
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<td></td>
<td>29</td>
<td>9.6</td>
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<td>25</td>
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<td>5.0</td>
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<td></td>
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<td>8.4</td>
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<td></td>
<td>29</td>
<td>11.1</td>
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<tr>
<td>35</td>
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<td>2.8</td>
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<tr>
<td></td>
<td>15</td>
<td>8.6</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>12.9</td>
</tr>
<tr>
<td></td>
<td>29</td>
<td>14.8</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Mineralized N was obtained by subtracting the initial nitrate–N, 6.67 mg N kg$^{-1}$ soil, from the total amount of nitrate–N after given days of incubation at 5 °C and 8% soil moisture content. Modified from Li et al. (1995).
Table 6  Effect of temperature and water content on mineralized N (mg N kg\(^{-1}\)) in soil after certain time of incubation

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Time (week)</th>
<th>Mineralized N</th>
<th>Amount of N mineralized at different water content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>8  15  22  29</td>
</tr>
<tr>
<td>15</td>
<td>2</td>
<td>Amount (mg N kg(^{-1}))</td>
<td>2.5 5.7 9.2 10.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Relative amount (%)</td>
<td>23.9 53.6 87.2 100.0</td>
</tr>
<tr>
<td>21</td>
<td>2</td>
<td>Amount (mg N kg(^{-1}))</td>
<td>10.2 18.8 24.3 33.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Relative amount (%)</td>
<td>30.7 56.3 72.9 100.0</td>
</tr>
<tr>
<td>25</td>
<td>2</td>
<td>Amount (mg N kg(^{-1}))</td>
<td>2.9 6.4 9.6 12.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Relative amount (%)</td>
<td>23.4 50.5 77.6 100.0</td>
</tr>
<tr>
<td>21</td>
<td>2</td>
<td>Amount (mg N kg(^{-1}))</td>
<td>18.9 29.6 37.6 50.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Relative amount (%)</td>
<td>37.4 58.6 74.4 100.0</td>
</tr>
<tr>
<td>35</td>
<td>2</td>
<td>Amount (mg N kg(^{-1}))</td>
<td>3.9 10.7 14.4 18.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Relative amount (%)</td>
<td>21.5 58.3 78.6 100.0</td>
</tr>
<tr>
<td>21</td>
<td>21</td>
<td>Amount (mg N kg(^{-1}))</td>
<td>28.4 49.2 68.9 84.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Relative amount (%)</td>
<td>33.6 58.1 51.4 100.0</td>
</tr>
</tbody>
</table>

Modified from Li et al. (1995).

Figure 6  Relationship between mineralized N and soil water content. Drawn with data from Ju and Li (1998).

for urea

\[ Y \approx 5.61 + 63.00X \ (r = 0.8918^*) , \]

and for ammonium chloride

\[ Y \approx 4.62 + 46.09X \ (r = 0.8825^*) , \]
where $Y$ is the nitrification rate (mg N kg$^{-1}$ d$^{-1}$), $X$ is the soil water content (%), and * and ** indicate significant at $p < 0.05$ and $p < 0.01$, respectively. Regression coefficients in the equations indicate the contribution of water increase by 1% to the increase of nitrification rate. Clearly, in the range of water contents of the experiment, the higher the water content, the faster

<table>
<thead>
<tr>
<th>Water content in soil (%)</th>
<th>NH$_4^+$ – N after given days of incubation (mg N kg$^{-1}$)</th>
<th>NO$_3^-$ – N after given days of incubation (mg N kg$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td><strong>No application of chemical fertilizers</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>32.0</td>
<td>10.7</td>
</tr>
<tr>
<td>15</td>
<td>29.8</td>
<td>5.3</td>
</tr>
<tr>
<td>18</td>
<td>28.3</td>
<td>4.8</td>
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<td>21</td>
<td>28.4</td>
<td>2.2</td>
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<td>24</td>
<td>27.8</td>
<td>2.4</td>
</tr>
<tr>
<td>27</td>
<td>26.7</td>
<td>0.8</td>
</tr>
<tr>
<td><strong>Application of ammonium chloride</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>59.0</td>
<td>75.8</td>
</tr>
<tr>
<td>15</td>
<td>54.2</td>
<td>61.5</td>
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<tr>
<td>18</td>
<td>39.6</td>
<td>44.2</td>
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<td>43.9</td>
<td>48.2</td>
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<td>35.2</td>
</tr>
<tr>
<td>27</td>
<td>35.5</td>
<td>28.3</td>
</tr>
<tr>
<td><strong>Application of urea</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>35.6</td>
<td>69.6</td>
</tr>
<tr>
<td>15</td>
<td>33.4</td>
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<td>27</td>
<td>31.0</td>
<td>22.6</td>
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<tr>
<td><strong>Application of ammonium bicarbonate</strong></td>
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</tr>
<tr>
<td>12</td>
<td>52.7</td>
<td>57.6</td>
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<tr>
<td>15</td>
<td>49.3</td>
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<td>13.7</td>
</tr>
<tr>
<td>27</td>
<td>25.7</td>
<td>10.9</td>
</tr>
</tbody>
</table>

*Initial soil ammonium–N was 24.8 mg N kg$^{-1}$ soil.*

Modified from Li et al. (1995).
the nitrification rate, and the more the transformation of ammonium–N into nitrate–N (Fig. 7).

The above results were obtained in the laboratory where soil moisture and temperature conditions were ideal and could be controlled, and are different from field conditions. To find if water has the same function for promoting the availability of nutrients in farm fields under natural conditions, Ju and Li (1998) conducted a field experiment, including irrigation and nonirrigation, and each at 5 N rates. Results claimed that irrigation increased crop yield and nutrient uptake, and therefore the differences in nitrate–N produced in the soil by irrigation were not comparable with that

<table>
<thead>
<tr>
<th>Water content in soil (%)</th>
<th>NH$_4^+$ – N after given days of incubation (mg N kg$^{-1}$)</th>
<th>NO$_3^-$ – N after given days of incubation (mg N kg$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1  3  6  11  17</td>
<td>1  3  6  11  17</td>
</tr>
<tr>
<td><strong>Application of ammonium chloride</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>27.0 65.1 43.5 38.7 0.0</td>
<td>3.3 1.7 3.8 18.0 37.9</td>
</tr>
<tr>
<td>15</td>
<td>24.4 56.2 21.5 0.0 0.0</td>
<td>2.4 6.3 40.4 86.5 93.1</td>
</tr>
<tr>
<td>18</td>
<td>11.3 39.4 2.1 0.0 0.0</td>
<td>0.3 17.4 63.8 90.4 93.6</td>
</tr>
<tr>
<td>21</td>
<td>15.5 46.0 3.8 0.0 0.0</td>
<td>0.5 19.6 65.1 84.6 100.1</td>
</tr>
<tr>
<td>24</td>
<td>9.4 32.8 4.4 0.0 0.0</td>
<td>0.3 17.8 65.2 84.7 100.3</td>
</tr>
<tr>
<td>27</td>
<td>8.8 27.5 0.6 0.0 0.0</td>
<td>0.4 20.2 74.5 88.3 98.3</td>
</tr>
<tr>
<td><strong>Application of urea</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>3.6 58.9 38.0 27.3 0.0</td>
<td>0.8 5.2 18.5 53.6 84.9</td>
</tr>
<tr>
<td>15</td>
<td>3.6 50.5 15.4 0.0 0.0</td>
<td>1.8 13.4 52.4 87.3 91.5</td>
</tr>
<tr>
<td>18</td>
<td>4.9 5.4 8.4 0.0 0.0</td>
<td>2.6 13.4 61.8 91.4 98.5</td>
</tr>
<tr>
<td>21</td>
<td>3.7 42.2 8.8 0.0 0.0</td>
<td>2.9 30.4 81.1 88.5 103.0</td>
</tr>
<tr>
<td>24</td>
<td>3.4 29.1 1.3 0.0 0.0</td>
<td>2.0 20.7 72.2 93.4 99.0</td>
</tr>
<tr>
<td>27</td>
<td>4.3 21.8 1.1 0.0 0.0</td>
<td>2.4 37.1 81.0 99.9 100.1</td>
</tr>
<tr>
<td><strong>Application of ammonium bicarbonate</strong></td>
<td></td>
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</tr>
<tr>
<td>12</td>
<td>20.7 46.9 34.7 19.5 0.0</td>
<td>1.8 1.3 15.3 52.0 62.8</td>
</tr>
<tr>
<td>15</td>
<td>19.5 49.5 16.9 0.0 0.0</td>
<td>0.7 0.6 41.1 87.5 90.1</td>
</tr>
<tr>
<td>18</td>
<td>12.5 34.5 2.3 0.0 0.0</td>
<td>1.6 15.7 69.1 88.5 96.9</td>
</tr>
<tr>
<td>21</td>
<td>2.0 19.8 0.7 0.0 0.0</td>
<td>1.1 18.8 69.5 38.1 99.4</td>
</tr>
<tr>
<td>24</td>
<td>6.4 11.3 0.3 0.0 0.0</td>
<td>2.1 28.8 84.2 88.4 101.8</td>
</tr>
<tr>
<td>27</td>
<td>1.0 10.1 0.9 0.0 0.0</td>
<td>1.8 30.4 79.6 91.1 101.8</td>
</tr>
</tbody>
</table>

*Residual N was obtained by subtracting the ammonium–N and nitrate–N in soil without fertilization from the corresponding amounts with fertilization under the same water content and at the same time. Modified from Li et al. (1995).*
in incubation. Even so, the irrigated field still retained more mineral N (total of ammonium–N and nitrate–N) than that without irrigation after wheat and maize harvest, respectively (Table 9). Obviously, the effect of water on the nutrient availability is the basis for supplying nutrients to plants, and adequate supply of water can make crops obtain sufficient nutrients, and thereby promote crop production.

3.2. Nutrient movement

During growing period, crops continuously absorb nutrients and water from soil with their roots, forming a depleted zone of nutrients and water around roots. This causes different content of water and nutrients between root zone soil and bulk soil, and thus water from the higher potential point with a distance from roots moves to the lower potential point close to roots, finally reaching its balance. Nutrients dissolved in soil water also move with water, leading to a decrease of nutrient concentration gradient. Water influences nutrient movement in three ways, interception, mass flow and diffusion,
and thus influences nutrient uptake by plants directly or indirectly. Barber (1984) pointed out that some nutrients such as Ca, Mg, and N were transferred by mass flow, whereas others such as P and K mostly by diffusion. Comprehensive review of literature by Mengel et al. (1969) concluded that mass flow, diffusion, and interception, respectively, contributed 82%, 7%, and 11% of the total N uptake of wheat on drylands. For sugar beet, spring wheat and spring barley, Reager et al. (1981) reported that the contribution of nitrate–N by mass flow to these crops occupied 100%, 40%, and 110%, respectively, of their total N uptake. The movement of mineral nutrients in soil is essential for crop uptake. Water deficit does not only affect nutrient amount in solution, but also the movement rate of mass flow and diffusion. The effect of water deficit on mass flow depends on the degree of decline in soil water potential, while that of diffusion largely on water potential changes.

Role of water on nutrient movement can be studied by determining nutrient concentration changes at different points of soil by using different water treatments over a period of time. If the nutrient concentration is different from the original, this shows nutrients being moved by water from one point to another. Otherwise, there is no movement or the movement cannot be measured (Barber, 1984). However, this method is only suitable for soil without plants. If plants are grown, their roots can extend toward different areas and directly absorb nutrients from points where roots reach, and this may drive nutrient movement in the soil. For this reason, separation of the contribution of water with that of plant roots to nutrient movement should be considered.

Song and Li (2006) conducted a field experiment on maize to determine the effect of water movement and root uptake of nutrients on \( \text{NO}_3^- - \text{N} \) and \( \text{NH}_4^+ - \text{N} \) transfer with four treatments: with and without limiting root-grown space, and with and without supplemental supply of water, using the method described by Li et al. (1994). Their results showed that both the root-grown space and water supply had a significant effect on reduction of nitrate–N concentration, but their effect on \( \text{NO}_3^- - \text{N} \) movement was different (Fig. 8). With irrigation, \( \text{NO}_3^- - \text{N} \) concentrations at all points measured were small with a difference of 6.5 mg N kg\(^{-1}\) between the highest and the lowest. This indicated that nitrate–N could be transferred as solute to plant root systems with water movement. Without irrigation, \( \text{NO}_3^- - \text{N} \) concentration sharply decreased from one point to another and the difference between the highest and lowest was 26 mg N kg\(^{-1}\). The nitrate–N concentration distribution was conformed to root distribution. On the average of three sampling times at 0–2, 2–4, 4–6, 6–8, and 8–10 cm distances from plants, root mass in the 20-cm topsoil layer were 13.9, 13.8, 7.5, 3.2, and 1.1 g m\(^{-2}\), and root areas were 45.6, 48.5, 37.8, 17.6, and 6.8 m\(^2\), respectively. Clearly, root mass and area were significantly decreased with distance from the plants, and so was nitrate–N concentration.
However, without supplemental water supply, there was a sharp decrease in NO$_3^-$ – N concentration from one point to another. The NO$_3^-$ – N decrease at different points was made by root direct uptake, and the great difference between adjacent points indicated that it was impossible for roots to promote nutrient movement from one point to another. This is more clearly for limited root-grown space treatments. Without irrigation, nitrate–N concentration difference between the highest and lowest was 43 mg N kg$^{-1}$; with irrigation, it decreased to 23 mg N kg$^{-1}$. Two obviously parallel curves formed between with and without supplemental water supply. In the two treatments, roots were almost entirely concentrated in 0–4 cm distance soil where water was exhausted. Therefore, there was a remarkably sharp decrease of nitrate–N concentration from 6 to 4 cm as shown on the abscissa, while beyond 6 cm, some water still existed, and thus nitrate–N-concentration difference at points 6, 8, and 10 cm was relatively small. The irrigation treatment had the same trend, but the difference between 4 and 6 cm was greatly decreased, and beyond point 6 cm, there was almost no difference. This again showed that roots promoted nutrient uptake, but was unable to directly promote nutrient movement or such role was too small to be measured. In contrast to nitrate–N, the transfer and distribution of ammonium–N were not influenced by root growth and soil water supply (Table 10). This may be caused by its movement mainly by diffusion, not by mass flow.

### 3.3. Nutrient efficiency

Although the nutrient uptake and water intake are two independent processes in nature, water status in soil greatly affects nutrient uptake and efficiency. Water deficit causes water stress to plants, inhibits plant root growth, reduces
absorbing area and capacity of plant roots, increases the viscosity of sap in hadromestome, and thereby, decreases nutrient uptake and transfer. Rego (1988) found that water stress reduced sorghum N uptake by 40%, and decreased N fertilizer use efficiency, as crop uptake of N from fertilizers was much lower than that without water stress. Zhao and Zhang (1979) demonstrated that when soil water content in pots was below wilting point, N fertilizer added to soil was almost useless to plants, the N recovery being only 1.9%, while when water content was adequate, the N recovery was increased to 35–39%. Li et al. (1994) showed that an adequate supply of water significantly increased N recovery by about 20% at any N rate (Fig. 9). Torbert et al. (1992) found that too much supply of water decreased N recovery. Overall, water content and its availability have a direct, great influence on plants themselves and on their nutrient uptake.

3.4. Nutrient distribution in plants

Soil water content also influences nutrient movement from roots to aboveground part of plants. The influence of water deficit on N distribution was different for different crops. Despite roots being mainly responsible for supply of N in most cases, water contributes a large portion of N to aboveground part. Dong (1992) found in apple trees that water deficit decreased leaf N content, promoted N transferring from new branches to old organs in trees without fructification; and due to different distribution, new organs contained much less N. Such changes were only found in newly growing branches of old trees with fructification. For cereals and leguminous crops, water deficit at later stages only reduced transfer of photosynthesis products from leaves, but N transferred to seeds and storage proteins were much less influenced. Singandhupe and Rajput (1990) revealed that extending time interval of irrigation for producing water stress resulted in a

<table>
<thead>
<tr>
<th>Time (m–d)</th>
<th>Sampling distance from plant (cm)</th>
<th>Root grown naturally</th>
<th>Root grown in nylon bag</th>
</tr>
</thead>
<tbody>
<tr>
<td>7–30</td>
<td>6.2ab 6.6a 5.6b 6.3ab 6.4a 8.3a 8.4a 8.1a 7.8a 8.0a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8–28</td>
<td>8.5a 8.8a 8.2a 8.6a 8.1a 13.2a 13.0a 13.0a 12.5a 12.8a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9–30</td>
<td>0.4a 0.3a 0.4a 0.2a 0.2a 0.2a 0.3a 0.3a 0.2a 0.2a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>5.2a 5.2a 4.7a 5.0a 5.3a 7.2a 7.2a 7.1a 6.8a 7.0a</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Data in the same line with the same letter indicate not significant at 0.05 level. Modified from Song and Li (2006).
decrease of N distributed to rice grain by 17%, but had no influence on its distribution to stems and leaves. Wang and Gao (1988) applied 60 mm water to winter wheat, and 70 mm to summer maize, and added N fertilizer at a rate of 113 kg N ha\(^{-1}\) to each in a semiarid area. Their results showed that irrigation increased grain N percentage of winter wheat by 0.07% and summer maize by 0.03%, while reduced that of stem by 0.12% and leaf by 0.14%. Li (2007) showed N allocation in wheat grain through mass flow by irrigation in a lysimeter experiment and revealed that wheat seeds obtained much higher N by the contribution of mass flow with irrigation compared to that without irrigation (Fig. 10). This indicates that water could significantly transfer N from other organs to seeds. Li et al. (1995) obtained similar results in a semiarid area. Whether irrigation increases or decreases grain N content, also depends on other nutrient supply and soil water amount.

**Figure 9**  Relationship of N fertilizer recovery to water supply. Drawn with data from Li et al. (1994).

**Figure 10**  Contribution of nitrate–N to N uptake of wheat through mass flow. Drawn with data from S. X. Li et al. (unpublished results).
Liu and Zhang (1991) reported that by irrigating 70 mm water and applying 239 kg N ha\(^{-1}\), grain N increased by 0.37% when adding 30 kg P\(_2\)O\(_5\) ha\(^{-1}\), and 0.07% when adding 120 kg P\(_2\)O\(_5\) ha\(^{-1}\). The reason for reduction of irrigation rate while increasing grain N content is assumed in that N uptake by winter wheat was higher than dry matter increase, and water deficit limited plant growth rate much higher than it did N uptake rate.

4. Effect of Water and Nutrients Interaction on Crop Yield

In dryland areas, the key point for crop production is rational combinative use of water and fertilizers (Guo et al., 1999; Zheng and Liu, 1995). Shimshi (1970) pointed out that the combined effect of water and N could be estimated based on Liebig’s law of the minimum to obtain approximate values. Assume that crop biomass production was \(Y_W\) under a water-limiting condition and that N supply was \(Y_N\) under an N-limiting condition. Under extremely low precipitation (less than 200 mm), \(Y_W < Y_N\), showing the biomass production being limited by water supply; and under precipitation in range from 200 to 400 mm, \(Y_N < Y_W\), showing N being the major factor affecting biomass production. Smike et al. (1965) found that when available water supply was less than 250 mm, grass production was very low, and the crop had little response to N fertilizer at any rate. However, when available water supply was increased to more than 400 mm, crop yield was raised, and the slope of a linear regression between yield and water amount was increased with the increase of N rate. Li and Zhao (1993) studied the relation of maize response to N and P fertilizers with water amount, and found that nutrient efficiency was increased by sufficient supply of water. Under water deficit, P fertilizer efficiency was more significant, while N fertilizer efficiency was sharply decreased. It is evident that there is an intense interaction between available water and fertilizer, and one being changed will likewise lead to the change of the other (Fan et al., 2003; Zhou and Li, 1995). As the mineralization of organic N and the nitrification of ammonium–N are linearly related with soil moisture under given conditions, water has double, or direct and indirect functions on plant growth and soil fertility (Standford and Epstein, 1974). Power (1971) considered that deficiency of water and N had an additive effect on crop yield decline. For example, smooth bromegrass (Bromus inermis Leyss) yield was reduced by 32% with water deficit, by 24% with N deficiency, and by 54% with both, the latter being almost equal to the addition.

Rational fertilizer rate was determined to a large extent by soil water supply. Leggett (1970) and Leggett et al. (1959) suggested a recommendation rate of N fertilizer for wheat based on precipitation in areas along the coast of the west Pacific Ocean. That is, rates being 20–40 kg N ha\(^{-1}\) for
those with annual precipitation <250 mm, 30–60 kg N between 250–380 mm and 60–80 kg N for those >380 mm. Dang et al. (1991) conducted field experiments in Weibei drylands, Shaanxi Province, to study the relation of water stored in soil profile before wheat being sown to N and P fertilizer rates in successive 8 years. Based on their results, they recommended to apply 69–98 kg N and 56–86 kg P₂O₅ ha⁻¹ in a precipitation deficit year (<200 mm), 93–137 kg N and 66–86 kg P₂O₅ ha⁻¹ in a normal precipitation year (200–250 mm), and 113–137 kg N and 68–99 kg P₂O₅ ha⁻¹ in a precipitation abundant year (>250 mm). Having adopted these rates, wheat yields were increased by 15–28% compared to that without fertilization. For rational estimation of N input, Li and Zhao (1993) suggested a precise method considering available water including water stored in soil before wheat being sown and precipitation infiltrated into soil during wheat growth period, WUE, degree of nutrient deficiency and current yield level. This estimation agreed well with the practical results.

For successful dryland agriculture, full use of groundwater and precipitation including eliminating runoff water or harvesting it for later use, and joint application of fertilizers with water-saving irrigation to play their synergic role have become a focusing point for investigation (Huang et al., 1990; Li et al., 1990c, 2001, 2005; Zhao et al., 1990). Li (1985) carried out an experiment with low irrigation norm in Luochuan County, Shaanxi Province, and found that declining the irrigation norm from 200 to 100 mm, wheat yield was not affected, and the irrigation result was to a great extent dependant on irrigation timing. Of the three irrigation times, prevernal (early spring) irrigation was better than that in winter and at grain filling stage. Mei and Tao (1993) found that with irrigation norm of 90 mm at four times, prewinter, elongation, booting, and filling stage, increased wheat yields by 27%, 45%, 8%, and 1%, respectively, thus elongation stage being the best. However, Chen et al. (1992) proved that irrigation just before sowing was superior over other stages during wheat-growing period.

The interaction of water and fertilizer is time dependant. Research has shown that irrigation of 60-mm water combined with application of 105 kg N and 52 kg P₂O₅ ha⁻¹ before sowing of wheat resulted in an increase of 585 kg grain ha⁻¹ as an interaction effect and, the interaction effect increased to 857 kg ha⁻¹ when irrigation amount was increased to 120 mm (Chen et al., 1992). However, irrigation with 75–220 mm water at other time for maize and wheat, the interaction effect was small, being 11–30 kg ha⁻¹ for winter wheat and 3–364 kg ha⁻¹ for maize. In some cases, negative interaction may occur. Although early application of water and fertilizer has been practiced, recently some results revealed that elongation stage might be the high efficient stage for winter wheat (Zhai and Li, 2005) and maize (Gao and Li, 2002; Gao et al., 2006). The different results obtained for the optimal time of application of water and fertilizer may relate to soil water and nutrient supply at different time, and without consideration
of their status at different time, it is impossible to obtain a common pattern for practical use. Wang et al. (1993) concluded that the significant interaction could not be realized for winter wheat and spring maize until high rate of fertilizer is applied. Li and Li (1994) showed that with adequate irrigation norm, interaction of water and nutrient increased with fertilizer rate increase, and high norm of irrigation was in a reverse situation.

For promotion of water and nutrient fully playing their role and realization of maximum yield, high quality, and high efficiency, while protection of the environment from fertilizer ill impact, one of important things is to fully understand and utilize their positive interaction (Fang et al., 2006; Li et al., 2001a,b, 2002a,b; Shaaban, 2006). Irrational combination may produce detrimental effect; the worst situation is negative interaction. For example, oversupply of water and N may delay crop maturation by encouraging excessive vegetative growth, weakening stems and subsequently lodging, in addition to wasting water and N by excessive uptake and overconsumption. Oversupply of water may lead to nutrient loss by leaching, while shortage of water supply may bring about high nutrient concentration in soil, leading to difficulties for crops to take up water and nutrients; and even making plants die before grain filling (“'haying-off” effect). Based on these considerations, attention should be paid not only to input of water and nutrients, but also to their rational combination. That is, for addition of water, one should consider nutrient supply, and for addition of nutrients, one should consider water coordination, so that limited nutrient and water can produce optimum effect. One should keep such an objective in mind and implement from beginning to the end in one’s planning and in production process.

5. Research Accomplishments, Gaps, and Future Needs

Studies related to the interaction effects of water and nutrients on crop yield and nutrient and WUE were initiated much later, because such research concerns multiple factors, and needs a number of treatments that are difficult to manage. Because of short supply of fresh water and fertilizer pollution becoming more serious in the world, there has been a focus on such investigations, and some achievements have been made in many countries, either in rainfed areas or in irrigated areas. One of the main nutrients for concern is N. In rainfed areas, the studies concentrate on N fertilizer and soil water interaction, attempting to mobilize soil water playing full role by rational N fertilization, and producing maximum positive interaction effect. In irrigated areas, however, the major emphasis lies on effects of irrigation and N fertilizer to obtain high sustainable yields, while saving water, controlling groundwater pollution, and reaching high efficiency.
By now, a variety of studies have been conducted on different aspects, and great progress has been made. Even though, there still exist a large number of issues that need further studies in the future.

Delineating drylands into different regions, and determining the priority issue in each region. Although water shortage is regarded as main constraint in dryland areas, it is not always true. In some regions or some fields in the same region, crops have no response to water application, but have a remarkable response to fertilization. This shows that nutrient deficiency is the major constraint; without supply of sufficient nutrients, water cannot play its role. For this reason, delineation of drylands into different regions, and determination of the major constraints related to water or nutrients in a given region are in the priority. It is impossible to have good harvest while reduction of pollution by application of either fertilizer or irrigation until the major constraint is found.

Determination of most efficient time or growth stage for input of nutrients and water to different crops. Each crop has different requirement and sensitivity to water and nutrients at different growth stages, and thus input of water and nutrients at different stages will have different effects. It has been reported that at early stage of a crop, deficiency of water produced a compensatory effect, and crop growth, photosynthetic rate, osmotic regulating ability, water-holding capacity of plant cell, energy metabolism, and physiological synthesis were all better in restoring water supply after a dry spell than those continuously retaining high water supply. For this reason, input of nutrient and water could achieve the high efficient use of water only at the most suitable time and nutrients. Based on such considerations, we should investigate the crop response to water and nutrient supply at different times, and determine the optimum efficient stage, and the stage at which deficiency of water or nutrients has no serious influence on crop yield, and the degree of deficiency that crops can tolerate or can allow to a certain extent. In such a way, we can take adequate measures to regulate water supply and to use suitable level of water and nutrients together at the most efficient stage. Such research has been done for some crops, but not for others.

Soil is the basic medium for plant growth, and is an important pool for supply of water and nutrients to plants. It is the soil that can change nutrient and water forms and availability, and only through which the water and nutrient role can be displayed. The input amount and frequency of water depend on soil water-holding capacity, and that of nutrients on soil nutrient-supplying capacity and the available quantity. Therefore, the effect of water and nutrient input is closely related with soil properties. Revealing available nutrient quantities, their release process, time, and the harmonious degree of its supply from the soil and that taken up by plants under various water conditions can provide basic information for guiding fertilization and determination of fertilizer amount and application time. Likewise, revealing soil capacity for water conservation and the availability of water added to
soils with different textures and its use efficiency under given conditions can clarify the direction and strategies for management. In addition to soil itself, tillage systems can change soil properties and thus play a great role on water storage, utilization, and availability. In dryland areas, both conventional and mulching tillage are used and such characteristics should be linked with water and nutrient management and strategies.

**Interaction mechanism of water and nutrients, especially that of nutrients in improving WUE.** Although a large number of studies have been carried out on the mechanism of the two factor interaction, such studies are often limited in a narrow range, most only in one aspect, and thus results are difficult to interpret the phenomenon of entire plant behavior. In fact, any stress from water or nutrients not only affects one property, but the entire process in plants. For instance, any stress can influence plant growth, decrease biomass, reduce photosynthetic efficiency, enzyme activity, and metabolism process and others. As a result, these studies can not reveal which was the primary cause and which was the secondary cause induced by the primary. For an understanding of the effect of nutrient deficiency on plant water, more attention should been paid on two aspects: water intake and plant retaining water. Radin and Boyer (1982) reported that N deficiency reduced the root membrane permeability of sunflower by 50%, leading to a serious inhibition of leaf swelling pressure and expanse at daytime. Recently, we observed that the same water stress had different effect on plant growth. That is, at high temperature, the influence was serious while at low temperature it was slight. At high temperature, the leaf temperature with fertilization was lower than that without fertilization while the transpiration velocity (rate) may not be higher. Obviously, in addition to the influence of water intake and consumption, fertilization may also maintain a proper temperature of plants. This phenomenon makes us assume that one of the main aspects by water stress may be caused by the reduction of transpiration and the rise of temperature in leaf. This may induce disorder of metabolism, and an important role of nutrient supply may be associated with the regulation of plant temperature and maintenance of plant normal metabolism. Investigation starting from such phenomena, we may reveal the nature of water to nutrient supply relation, and that of the supply of nutritional materials in eliminating the dryness stress.

6. **Summary and Conclusions**

China’s drylands cover vast regions in northern territory. Low precipitation and uneven distribution result in deficit of water. Sparse vegetation coverage plus windy climate and frequent rainstorms have led to serious wind and water erosion, which is further intensified by human activities. Two constraints exist for crop production: shortage of water supply, and
nutrient stress by soil degradation derived from severe erosion. Limited water resources have not been fully used in the areas, and have a certain potential for agricultural production.

Nutrient input is essential for crop production on drylands. Addition of fertilizers, particularly organic fertilizers, can enhance soil organic matter, raise soil water storage capacity, promote root growth, increase root length, make roots absorb more water from deep soil layers, and thereby increase plant tolerance to drought, and improve plant physiological activities such as plant water status, osmotic pressure regulation, high activity of nitrate reductase in plant leaves, and high photosynthesis and transpiration intensity but decrease evaporation. All these benefit plants in absorbing water and nutrients and optimize their use efficiency.

Effective water management can increase nutrient availability, transformation of nutrients in soil or from fertilizers, promote nutrient uptake by plants and nutrient use efficiency, transfer a large portion of N to aboveground part, affect plant nutrient composition, and mineral nutrient movement from soil to roots and then from roots to aboveground parts of plants. Water deficit causes water stress in plants, inhibits plant root growth, reduces absorbing areas and capacities of plant roots, increases the viscosity of sap in hadromestome, and thereby decreases nutrient uptake, transfer, and efficiency.

Adequate supply of water and nutrient can increase efficiency of both and produce good interaction. However, oversupply of either or both may delay crop maturation by encouraging excessive vegetative growth, while deficit of water may result in high nutrient concentration in soil, making it difficult for crops to take up and use both water and nutrients, and in a worst case, plants may die resulting in "haying-off" effect. Since water supply and nutrient efficiency are closely related, balanced application of nutrients, and determination of their types, ratios, amounts, timing, and methods should be based on the nutrient-supplying capacity and water status of soil.

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REFERENCES


(Shaanxi Agricultural Ministry), pp. 73–76. Shaanxi People’s Publishing House, Xi’an, Shaanxi, China.


Unger, P. W. (1975). “Relationships Between Water Retention, Texture, Density, and Organic Matter Content of West and South Central Texas Soil.” Texas Agricultural Experiment Station, College Station, TX.


