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# Implications and Ways to Enhance Nutrient Use Efficiency Under Changing Climate

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## ABSTRACT

Introduction of fertilizer and fertilizer responsive crop varieties paved way for green revolution and it was responsible for doubling the crop production to meet the food grain needs of ever growing global population. Over the four decades reduced use of organic manure and injudicious use of inorganic fertilizer led to declining trend of organic carbon and pose serious global warming threats to the environment as well as mankind.

Among the mineral fertilizer, nitrogen fertilizer occupies a major share in the global scenario in terms of production and application, it is the important crop responsive fertilizer at the same time overdose and improper application may cause $N_2O$ emission and $NO_3$ contamination in groundwater. Phosphorus and potassium fertilizers are applied in large quantity next to nitrogen. Continuous use of primary nutrients and negligence of secondary (Ca, Mg and S) and micronutrients (Fe, Zn, B, Cu, Mn and Mo) application exposed severe multi-nutrient deficiency in the soil. Changing climate highly influence the crop phenology, physiology, root morphology and uptake mechanism. Therefore it is inevitable to understand the climate change mediated changes in soil nutrient availability and plant nutrient uptake in different ecosystem.

In the past two decades decreasing trend of nutrients utilization efficiency and deficiency of micronutrients rendered the land barren under changing climate. But direct impact of climate change on nutrient availability and uptake mechanism has not been understood. In this context, developing or modifying the management strategies to enhance the use efficiency of applied nutrients is of paramount importance. Climate smart management techniques such as appropriate timing of nutrient application, using efficient irrigation practices, converting to nitrogen-fixing plants as cover crops and crop rotation. Employing advanced fertilization techniques such as controlled-release fertilizers and nitrification inhibitors enhances crop productivity in sustainable manner. All these management techniques need to be tested through different quantitative measures of nutrient use efficiency of

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crops under different soil conditions. Development of smart fertilizer delivery system for all the crops in different cropping system needs to be explored. Tailoring of higher nutrient use efficiency cultivars of different crops should to be accelerated using advanced breeding techniques to mitigate adverse influence of climate change on crop productivity improvement.

**Keywords:** Biofertilizer, climate change, fertilizer, nutrient use efficiency, soil management

## 1. IMPORTANCE AND PROSPECTS OF FERTILIZER AND BIOFERTILIZER IN AGRICULTURE

Global food production now faces greater challenges than ever before due to changing climate, increasing land degradation and decreasing nutrient use efficiency. There is no single solution to delivering increased crop productivity while improving resource use efficiency and protecting environmental quality. United Nations convention on climate change defined climate change as "change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods (IPCC, 2007).

Agricultural crops are exposed to many stresses that are induced by both biotic and abiotic factors. These stresses decrease yields of crops and represent barriers to the introduction of crop plants into areas that are not suitable for crop cultivation. The occurrence and activity of soil microorganisms are affected by a variety of environmental factors as well as plant-related factors. Abiotic stresses include high and low temperature, salinity, acidity, drought, flooding, ultraviolet light and heavy metals. The yield losses associated with abiotic stresses can reach 50 to 82 per cent depending on the crop.

Atmospheric rise of $CO_2$, $N_2O$ and $CH_4$ affect agriculture and food production especially during the last decade by increasing global temperature, which led to uncertainty in monsoonal rainfall and increasing the frequency of drought, storms, floods, forest fires and insect pest and diseases besides deteriorating plants and animals habitats. In total climate change severely affect the crop productivity and livelihood security of the farmers in semi-arid tropics of the globe. Among the agriculture practices, fertilizer application plays a major role in green house gases (GHGs) emission. Under changing climate carbon sequestration and reducing $N_2O$ emission through suitable soil and agronomic management techniques are the need of the hour to maximize the nutrient use efficiency and crop yield.

Nutrient mining is a major cause for low crop yields in parts of the developing world. Especially nitrogen and phosphorus move beyond the bounds of the agricultural field because the management practices fail to achieve good congruence between nutrient supply and crop nutrient demand. If it is unchecked, it severely affects the food production. Hence, increasing nutrient use efficiency continues to be a major challenge for agriculture.

Changing climate highly influences the plant growth and nutrients must be available in sufficient and balanced quantities. Soils contain natural reserves of plant nutrients, but these reserves are largely in unavailable forms to plants and only a small portion is released each year through biological activity or chemical processes. This release is too slow to compensate for the removal of nutrients by agricultural production and to meet crop requirements. Therefore, fertilizers are designed to supplement the nutrients already present in the soil. The use of chemical fertilizer, organic fertilizer or biofertilizer has its own advantages under changing climate and its advantages are to be integrated in order to make optimum use of each type of fertilizer and achieve balanced nutrient management for different crops under this starving situation.

## 2. SCENARIO OF FERTILIZER AND BIOFERTILIZER IN THE GLOBAL CONTEXT

### 2.1 Nitrogen

World nitrogen fertilizer demand was to increase at an annual rate of about 2.6 per cent upto 2012, for an overall increase of 11 million tonnes N. North America will remain the world's largest nitrogen importer. Consumption in the sub-region is projected to grow at about 1 per cent per year and at almost 3 per cent per year in Latin America. West Europe is projected to show zero growth, while West Asia is forecasted to record the fastest growth in the world at almost 5 per cent per year. Nitrogen fertilizer consumption is also projected to grow at a high annual rate of over 4 per cent in Africa and West Asia. South Asia's nitrogen fertilizer consumption is projected to increase by over 3 per cent per year. The share of urea in nitrogen fertilizer consumption is expected to continue to increase.

### 2.2 Phosphate

The expected annual growth rate in world demand for phosphate fertilizers was about 2.8 per cent until 2012 (IFA, 2011), for an increase of 5 million tonnes $P_2O_5$ compared with 2006. About 58 percent of this growth will take place in Asia; consumption growth in South Asia is projected to surpass growth in East Asia at almost 5 per cent per year. Rapid growth will also occur in East Europe and Central Asia and in Latin America. Phosphate fertilizer consumption will continue to decline marginally in West Europe.

### 2.3 Potash

World demand for potash fertilizers is projected to increase at an annual average rate of about 2.7 per cent, equivalent to an increment of 3.5 million tonnes. Major fertilizers and raw materials producing countries and its capacity are given in the Fig. 1.

Global use of N and P fertilizer increased 7- and 3.5-fold between 1960 and 1995 and we experience the consequences of this increase in greatly magnified ecological problems. Clearly, we cannot just project the demand for N and P fertilizer to triple by 2050, but have to consider all means at our disposal for the intensification of agricultural production and opt for soil and ecology adapted versions. Globally, crop systems have low nutrient use efficiency with 30–50 per cent and 45 per cent of applied N and P fertilizers respectively utilized by crops (Tilman *et al.*, 2002).

### 2.4 Biofertilizer

The green revolution saved us from famine; now environmental sustainability is at the heart of innovation in crop production. Next-generation crop systems will increasingly rely on nutrients that supplement or replace synthetic N fertilizers and natural deposit resources. Nutrient efficient

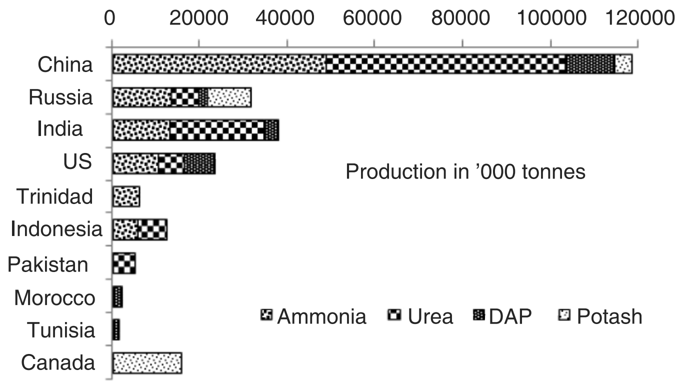


**Fig. 1** Global fertilizer production trend in 2010

crop systems have to integrate microbial symbionts, appropriate soil biota and diverse nutrient sources to combat effect of climate change on soil health and crop production.

Soil microorganisms play a significant role in regulating the dynamics of organic matter decomposition and the availability of plant nutrients such as N, P and S. It is well recognized that microbial inoculants constitute an important component of integrated nutrient management that leads to sustainable agriculture. Biofertilizers represent a promising alternative to synthetic fertilizers. It includes microorganisms, such as bacteria, fungi, cyanobacteria, algae and their metabolites that are capable of enhancing soil fertility, crop growth and yield. Application of biofertilizers to agricultural land could increase the amount of carbon stored in the soils. It contributes significantly to the reduction of greenhouse gas emissions by eliminating the requirement of fossil fuels for production of N: P: K fertilizers. Further, its application through designer seed mechanism and soil application enhance the plant growth promoting bacteria and fungi which are directly responsible for applied fertilizer transformation and its use efficiency. Nowadays farmers and agriculturists are showing more interest in biofertilizers application than the agrochemicals as they are found to be harmful to the soil. The importance of biofertilizers has increased in an increasingly eco-conscious world. Besides, soil quality is improved through the application of these environmental friendly fertilizers and also it contributes in reducing the negative impact of global warming.

## 3. IMPLICATIONS OF FERTILIZERS AND BIOFERTILIZERS UNDER CHANGING CLIMATE

### 3.1 Response of Fertilizer Under Changing Climate

Soil degradation is occurring due to inadequate and imbalanced fertilization leading to nutrient mining and development of second generation problems in nutrient management. The estimated supply-demand gap was about 1.8 million tonnes of N and 1.9 million tonnes of phosphorus by 2011-12 and it will be increased in the coming years ahead. Globally it is of concern that the partial factor productivity of fertilizers has been continuously declining. The efficiency of fertilizer N is only 30-40 per cent in rice and 50-60 per cent in other cereal crops. The efficiency of fertilizer P is 15-20 per cent in most of the crops and K use efficiency is 60-80 per cent. Low nutrient recovery efficiency not only increases the cost of crop production but also causes environmental pollution.

Inadequate application of potassium combined with over-excessive application of nitrogen is a serious problem in modern intensive agricultural production systems. It leads to large N losses, environmental pollution and low nitrogen use efficiency. Although fertilizer consumption is increasing quantitatively, the corresponding yield increase per unit of nutrient has diminished over the years (Sharma and Sharma, 2011). The response ratio in foodgrain crops in irrigated areas in India (Fig. 2) substantially declined between 1960 and 2008 (Biswas and Sharma, 2008). Improvement of the NUE is of paramount importance both for economical as well as environmental reasons. The overall fertilizer response in irrigated areas of the country decreased nearly three times from 13.4 kg grain per kg NPK in 1970 to 3.7 kg grain per kg NPK in 2005.

Efficient use of nutrient inputs on a farm is important for improving crop productivity and mitigating the climate change. Enhancing nitrogen efficiency directly responsible for nitrous oxide emission reduction and reducing agriculture's contribution to climate change. Nutrient use efficiency of N, P, K and Mg in all plant parts was significantly increased at elevated $CO_2$ (SamanSeneweera, 2011).

According to Pregitzer and King (2005), changes in plant and microbial function will be very tightly coupled to changes in soil temperature and moisture in the future and these ecological interactions will play critical roles in nutrient availability and net ecosystem productivity. Impact of climate change on nutrient availability and its use efficiency is illustrated in Fig. 3.

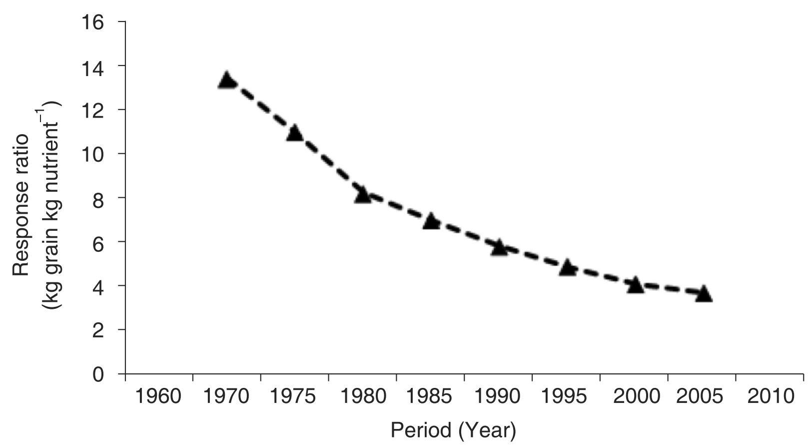


**Fig. 2** Fertilizer response of foodgrain crops in irrigated areas in India

Soil degradation associated with inorganic N fertilizer includes loss of soil organic matter (SOM), declining soil pH and declining crop yields (Guo *et al*., 2010). Loss of SOM in degraded agricultural soils affects aeration, structure, nutrient availability and microbial diversity. Preventing SOM depletion has been a challenge since the beginning of intensive agriculture. Recycling of organic residues to soil contributes to replenishing of SOM. Adverse effects of continued

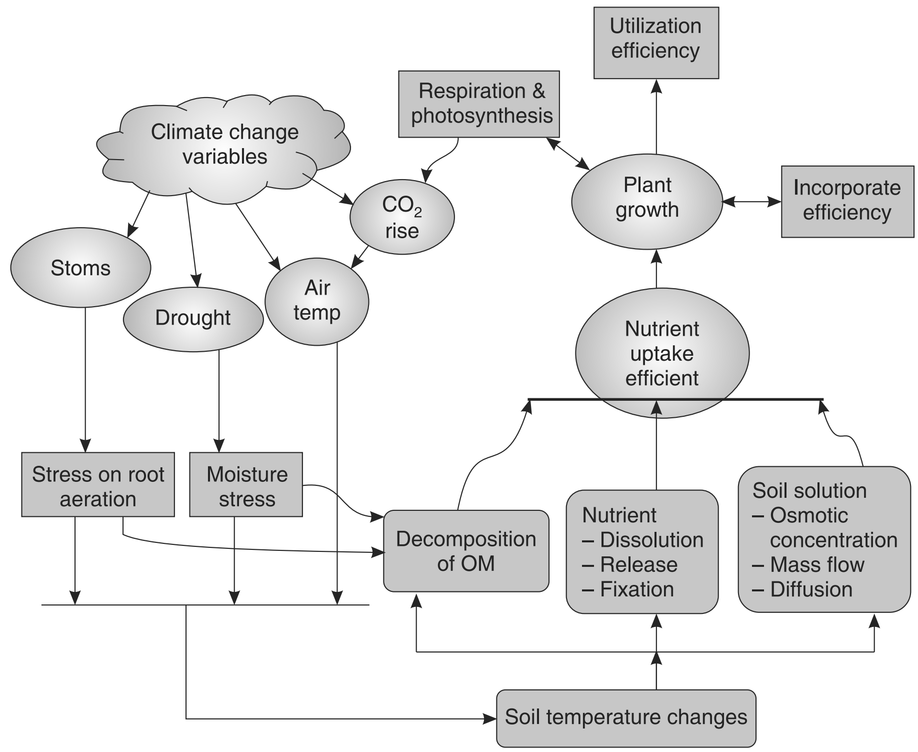


**Fig. 3** Impact of climate change on nutrient availability, uptake and its use efficiency

application of synthetic fertilizers was aptly put by proverb: fertilizer makes the father rich and the son poor". But nitrogen has been reported to play an important role in soil C storage, both by promoting crop dry matter production and by chemically stabilizing C in the soil. Many experiments have shown that fertilizing crops with N results in higher levels of soil C over time. In 25-year study, Wilts *et al*. (2004) reported that total soil organic C declined for all treatments, but at a slower rate in the fertilized treatments than in the unfertilized control and it is depicted in Fig. 4.

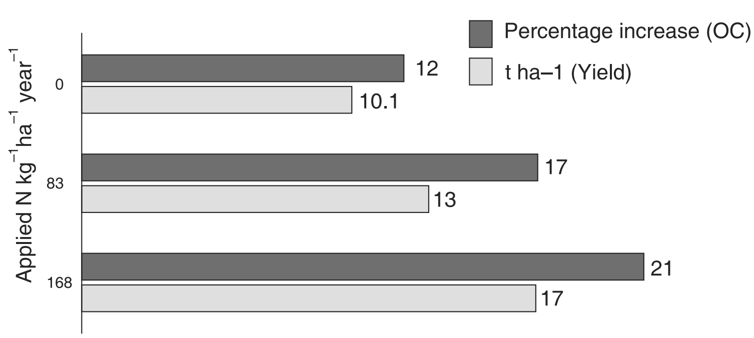


**Fig. 4** Soil organic carbon builds up in 30 years corn field and yield performance

SOM is a key factor for soil fertility due to its role for soil structure, biological processes and nutrient cycling, providing sink and source for nutrients and energy for soil organisms and plants. Long-term trials have shown that yields are often higher in soils with higher SOM (Johnston *et al*., 2009). Organic cropping systems that supply predominantly organic materials and legumes as nutrient sources have been compared with conventional systems resulted that average yields of 5 to 34 per cent lower in organic compared with conventional systems (Seufert *et al*., 2012). Compared to conventional agriculture, organic systems are more likely to be N limited, which may reduce off-site N losses.

Improving the efficiency and effectiveness of crop N use can potentially reduce $N_2O$ emissions, by reducing the potential for elevated residual $NO_3$- N in the soil profile (Dobermann, 2007; Dobermann and Cassman, 2005). Better nutrient management, including fertilizer best management practices, can potentially increase crop N recovery and minimize the cascade to air and water resources. Improvements in N use efficiency can also lead to greater C sequestration and reductions in $CO_2$ emissions.

Both N fixation and denitrification are affected by temperature, N availability and soil moisture. In developing regions, N fertilizer use was lesser in the early 1960s and increased exponentially during the course of the green revolution. The large increase in N use since the 1960s resulted in a steep decrease in Partial Factor of Productivity of Nitrogen (PFPN) in all developing regions. Regional N rates on cereals range from less than 10 kg N/ha in Africa to more than 150 kg N/ha in East Asia and with the exception of Africa, PFPN continues to decline in all developing regions at rates of –1 to –2 per cent per year (Dobermann and Cassman, 2005). The very high PFPN in Africa (122 kg/kg N applied) and Eastern Europe and Central Asia (84 kg/kg N applied) are indicative of unsustainable soil N mining due to low N rates used at present. In India, PFPN seems to have levelled off in recent years, but in many other developing countries it continues to decline because public and private sector investments in better technologies, services and extension education are far below those made in developed countries. Except in research and limited on-farm demonstrations, there are no documented cases for country-scale increase in N use efficiency. Global fertilizer production trend was explained in Table 1.

Controlled release or enhanced efficiency of fertilizers generally work by controlling the speed at which fertilizer or a coating applied to it, dissolves in soil water. By affecting the timing of nitrogen release from fertilizer, these compounds have the potential to reduce the loss of nitrogen and therefore improve nitrogen use efficiency. Similarly, soluble fertilizers formulated with inhibitors reduce or block the conversion of nitrogen species by affecting specific types of microbes involved. This helps to keep nitrogen in the form of ammonium longer, encouraging uptake by crops and helping to prevent $N_2O$ emissions from either nitrification or denitrification.

The different nitrification inhibitors such as dicyandiamide, nitrapyrin and wax coated $CaC_2$ in combination with urea were tested to quantify the nitrous oxide emission in corn, rice, wheat and barley crops. Among the N inhibitors urea in combination with wax coated $CaC_2$ reported low $N_2O$ emission over the urea alone application (Mosier *et al*., 1994).

Exploitation of specially designed mineral fertilizer such as nitrification inhibitors, coated fertilizer and urease inhibitors certainly curtail the global green house gases (GHGs) emissions under variable climate.

**Table 1** Global N fertilizer production and N use efficiency in cereals

| *Countries* | *Total fertilizer production (Mt)* | *N application rate (kg N/ha)* | *N use by cereals (Mt)* | *Total share of N consumption by cereals (%)* | *Partial productivity of N (kg/kg)* |
|---|---|---|---|---|---|
| North America | 12.5 | 112 | 8.3 | 66 | 45 |
| North East Asia | 0.9 | 89 | 0.3 | 32 | 68 |
| West Europe | 9.5 | 113 | 4.3 | 45 | 49 |
| East Europe Central Asia | 4.9 | 25 | 2.5 | 21 | 84 |
| Oceania | 1.3 | 48 | 0.9 | 67 | 40 |
| Africa | 1.4 | 9 | 0.8 | 56 | 122 |
| West Asia North East Africa | 4.2 | 68 | 2.4 | 56 | 34 |
| South Asia | 14.6 | 58 | 7.3 | 50 | 41 |
| South East Asia | 4 | 65 | 2.8 | 71 | 49 |
| East Asia | 24.9 | 155 | 14.5 | 58 | 31 |
| Latin America | 5.1 | 55 | 2.7 | 53 | 53 |
| World average | 83.2 | 10 | 46.7 | 57 | 44 |

Combined application of organic and inorganic nutrients enhanced the yield of groundnut and maize crops in India. Integrated nutrient management practices in the System of Rice Intensification enhanced the crop growth and yield by maintaining favourable soil physio-chemical properties and high water productivity, which in turn lowering cost of production. Application of farmyard manure along with inorganic fertilizers maintained SOM and long-term productivity with high microbial biomass in groundnut based rain-fed cropping system (Kannan *et al.*, 2011). The integrated use of organic and synthetic fertilizers with bio-inoculants may be the best option for improving the soil fertility and crop production under changing climate. Some of the report explained that organic sources application not able to synchronize nitrogen release with crop demands and may increase $N_2O$ emissions in comparison with synthetic fertilizers under certain circumstances (Flynn, 2009).

Practice of integrating green manures, planting nitrogen-fixing crops and incorporating livestock manures into the soil, decreases the amount of nitrogen lost through run-off and emissions of nitrous oxide. Applying these management practices can serve adaptation needs by improving soil quality and also decreasing farmers' costs and dependence on outside inputs.

Phosphorous requirement of plants may increase under the rising atmospheric $CO_2$ and temperature as indicated by the significantly higher uptake of P despite the reduced yield of wheat under elevated $CO_2$ and temperature. Although certain compensatory responses by plants, in terms of better root growth and higher recovery efficiency of applied P, may be elicited in response to higher P requirement. The benefits of such responses may get offset by the reduction in P utilization efficiency and overall P use efficiency under elevated carbon dioxide and temperature. Therefore, it underlines the need of P-efficient crop cultivars and suitable nutrient management practices for sustaining crop productivity in a changing climate (Manojkumar *et al.*, 2011).

Plant nutrient acquisition in an elevated $CO_2$ environment will be regulated by the interaction of compensatory adjustments in root growth, lifespan, physiology and symbiotic association. P concentration in rice grown under elevated $CO_2$ was found to decline by 5 per cent compared to 28 per cent decline for Zn and 17 per cent for Fe (Seneweera and Conroy, 1997). In his recent study, found no change in P concentration in rice grown under elevated $CO_2$. Grain P concentration decreased by 3.7 per cent compared to 30 per cent decline for Fe and 15.1 per cent for Zn (Fangmeier *et al.*, 1997). Hence higher doses of P fertilization are considered inevitable to sustain higher crop productivity under elevated $CO_2$.

Some of the study results confirming that there is no reduction or very small reduction in grain P content in comparison to severe reduction in Zn and Fe concentration. Grain elemental composition of five wheat cultivars grown under elevated $CO_2$ showed that 2.5 per cent decline in P concentration as against 15 per cent for Fe and 21 per cent for Zn (Loladze, 2002).

Optimized fertilizer management and its significance in climate change

- Fertilizers are used to maximize the increase crop yields, but it consumes more fossil fuel energy for their production. Since fertilizer use itself involves energy consumption, so as to reduce GHGs emission optimum fertilizer application need to be popularized.
- Application of fertilizer enhances the net primary productivity of cropland, which in turn, increases the return of crop residue C to the soil.
- Demand of biofuels increases the need for higher biomass production per unit of land area, it also increases fertilizer use. Efficient fertilizer management is to offset the net energy production or fossil fuel use under prevailing climatic variability.

## 3.2 Response of Biofetilizer Under Changing Climate

Biofertilizers are important components of integrated nutrients management. These potential biological fertilizers would play a key role in productivity and sustainability of soil and also protect the environment and cost effective inputs for the farming community under changing climate. Biofertilizers are products containing living cells of different types of microorganisms and it is applied through seed, soil and plants, which colonize the rhizosphere, interior of the plant and promotes growth by converting nutritionally important elements such as nitrogen, phosphorus from unavailable to available form through biological process such as nitrogen fixation and solubilization of fixed soil reserved phosphate. Many studies have shown that biofertilizers maintain the soil health and enhances crop yield through the following means:

- increased nutrient transfer
- better crop yield
- enhanced population of beneficial microorganisms
- stabilization of soil aggregates

Nitrogen fixing organisms are used in biofertilizer as a living fertilizer composed of microbial inoculants or groups of microorganisms which are able to fix atmospheric nitrogen. They are grouped into free-living bacteria (azotobacter and azospirillium), the blue green algae (BGA) and symbionts such as rhizobium, frankia and azolla (Gupta, 2004). Many experimental reports revealed that rice yields are increased by 0.5-2 t $ha^{-1}$ due to azolla application. Azobacter and Azospirillum also fix atmospheric nitrogen in cereal crops without any symbiosis. El-Komy

(2005) demonstrated the beneficial influence of co-inoculation of *Azospirillum lipoferum* and *Bacillus megaterium* for providing balanced nitrogen and phosphorus nutrition to wheat plants. Combined application of organics and blue green algae not only recorded higher yield, but found to emit less methane in paddy cultivation than the application of organics alone. Application of BGA and *azolla* reduced methane flux without reducing rice yields and can be used as a practical mitigation option for minimizing the global warming potential of rice ecosystem and increasing N use efficiency.

Phosphate solubilizing bacteria (PSB) are capable of transforming soil P to the forms available to plant. Microbial biomass assimilates soluble P and prevents it from adsorption or fixation (Khan and Joergesen, 2009). Among the soil bacterial communities, ectorhizospheric strains from pseudomonas and bacilli and endosymbiotic rhizobia have been identified as effective phosphate solubilizers. Strains from bacterial genera pseudomonas, bacillus, rhizobium and enterobacteria along with penicillium and aspergillus fungi are the most powerful P solubilizers (Whitelaw, 2000).

Soil application of bacteria with mycorrhizae increased the biological yield and miximized the grain weight of barley (Mehrvarz *et al*., 2008). Single and dual inoculation of biofertilizer with P fertilizer was 30-40 per cent better than P fertilizer alone for improving grain yield of wheat and dual inoculation without P fertilizer improved grain yield up to 20 per cent against sole P fertilization (Afzal and Bano, 2008). Rhizospheric microorganisms can interact positively in promoting plant growth, as well as N and P uptake. Triple inoculation of *Bradyrhizobium,Glomus fasciculatum* and *Bacillus subtilis* enhanced the seed yield to the tune of 24 per cent in greengram (Zaidi and Khan, 2006).

Mycorrhizal symbioses are nearly ubiquitous in plants and play important roles in mobilization of nutrients from organic matter and acquisition of diffusion limited nutrients, mainly P and Zn. Numerous studies reported increased resource allocation to mycorrhizal roots in plants exposed to elevated $CO_2$ and this may reflect the relative importance of edaphic constraints to plant growth in most ecosystems. Arbuscular mycorrhizal fungi enhance the decomposition of organic material and retrieve organic N and P for plants. Root exudation of protons, organic acids and extracellular enzymes responsible for improved use of organic nutrients over the inorganic fertilizers. Atmospheric $CO_2$ enrichment increases the production of a protein called glomalin by common root-dwelling soil fungi and this protein provides a wide range of benefits, including enhancing the stability of soil aggregates, which improves the capacity of soils to store more carbon and better preserve it from further decomposition and decreasing the risk of potentially toxic elements to soil microorganisms and plants.

Biochar application change soil nutrient availability and bio-available nutrients such as N, P and metal ions by altering the soil physicochemical properties. Increases in soil nutrient availability may result in enhanced host plant performance and elevated tissue nutrient concentrations in addition to higher colonization rates of the host plant roots by arbuscular mycorrhizal fungi (DeLuca *et al*., 2006).

Different mechanisms of rhizosphere microbes positively responded for plant growth and crop yield. Plants can utilize benefits provided by the microbes; agricultural productivity to be enhanced by fully exploiting beneficial microbial benefits such as production of phytohormones, induced systemic resistance and alteration of plant functional traits.

## 3.3 Nutrient Interaction Under Changing Climate

Nutrient availability may provide one of the most critical controls on the net balance between plant and soil processes. In systems with low soil nitrogen availability, additional nitrogen from deposition is thought to be one of the major causes of increases in crop growth and soil carbon storage in the semi-arid environment. Nutrients such as nitrogen and phosphorus are critical in controlling ecosystem carbon balance as most natural systems are nutrient limited. Thus, the limited availability of nutrients can hamper the dry matter production due to higher temperatures or $CO_2$ atmospheric concentrations under changing climate. Availability of nitrogen in many ecosystems is now significantly enhanced due to atmospheric nitrogen deposition and this has major consequences for the ecosystem carbon balance.

Unfortunately, the effect of N deposition and nutrient availability in general, on soil organic matter turnover remains largely overlooked by existing models. Assumptions that increased N availability will reduce organic matter decomposition rates. Implications of this greatest effect of nitrogen on carbon storage may be expected in carbon-rich, nutrient-poor systems due to both an increase in production and a decrease in the decay rate of an enlarged recalcitrant organic matter pool. The effects are likely to be considerably smaller in agriculturally managed systems, where nitrogen inputs are higher and where regular soil tillage stimulates soil organic matter turnover. Improving N use efficiency and reducing N fertilizer inputs in crop production is an important goal given the energy and greenhouse gas costs of N fertilizer manufacture and the potency of $N_2O$ as a greenhouse gas 310 times that of $CO_2$. The basic management goal is to reduce N losses from the soil plant system, especially those by denitrification which is a major source of $N_2O$ emissions from soil. Key parts of improving N efficiency are to avoid excessive N applications and to synchronize N supply with crop demand. The latter is more easily achieved when nitrogen is supplied from fertilizer than from organic N sources, where release is controlled by biological mineralization processes. In general, release of N from organic N sources continues beyond the period of crop production and can contribute to leaching losses and off-site pollution problems, including additional generation of $N_2O$. Research has also shown that emissions of $N_2O$ from cropland are higher when manure is used as the N source (Duxbury *et al*., 1982)

K cycling and recycling play an important part in $NO_3^-$ translocation from root to shoot as counter ion and assimilate loading in the phloem. Enhancement in uptake of N through K application ultimately helps in increasing the NUE. Yield response to K application depends to a great extent on the level of N nutrition and the interaction is normally positive (Brennan and Bolland, 2009). A gain of 20 per cent in nitrogen use efficiency can easily be achieved by balanced fertilization with K. A positive relationship between N and K exists for the uptake and utilization of N by plants to form protein and amino acids which ultimately affect the quality and yield of crops. Balanced use of N, P, K and micronutrient fertilizers in cereals and other crops will not only prove more profitable for farmers but also lead to reduced environmental degradation and combat the effect of climate change.

Indirect effects of climate drivers on nutrient availability:

(i) In experimental warming, changes in nitrogen availability have been shown to increase the risk of soil carbon loss. In tundra systems warming results in an increase in the abundance of shrubs (Sturm *et al*., 2005). This change in vegetation structure causes higher winter soil temperatures and resulting increase in microbial activity and plant-available nitrogen further promotes shrub abundance and a positive feedback loop.

(ii) Drought has been shown to reduce uptake of phosphorus and other nutrients by trees in a Mediterranean system thus increasing P-limitation of growth (Sardans *et al*., 2008).

(iii) Extreme weather conditions affect the dynamics of nutrient release from litter may also be responsible for oscillations in annual net primary production indifferent ecosystem.

(iv) Patterns across rainfall gradients indicate that concentration of extractable nutrients generally decrease with precipitation with a widening of carbon and nutrient ratios (Austin and Vitousek, 1998). This suggests an asynchrony of carbon and nutrient dynamics driven by the different sensitivity of photosynthesis and decomposition to temperature and water availability but also the effect of rainfall and temperature on other abiotic and biotic processes specific to individual elements.

## 4. FACTORS GOVERNING THE FERTILIZER AND BIOFERTILIZER USE EFFICIENCY

### 4.1 Abiotic Factors Affecting Nutrient use Efficiency

#### 4.1.1 *Effect $CO_2$ Concentration on Nutrient Uptake*

Uptake of $NH_4$ and $NO_3^-$ seems to be differentially sensitive to high $CO_2$, which could influence ecosystem path towards N saturation. Increased soil temperature might increase N and P uptake capacity to a greater extent in species from warm and fluctuating soil habitats than in species from cold and stable soil environments. The few available data also indicate that increased soil temperature elicits a differential effect on uptake of $NH_4^+$ versus $NO_3$ (Bassirirad, 2000). Root is the main organ involved in water and nutrient uptake and as one of the major sinks for assimilated C, roots play a critical role in determining plant and ecosystem responses to various aspect of global change ranging from N deposition and elevated $CO_2$ (Van Noordwijk *et al*., 1998).

Elevated $CO_2$ accelerates the crop growth through increased photosynthetic activity. Higher growth rate increase the plant nutrient demand and uptake capacity. A large number of $CO_2$ studies have demonstrated both a short-term stimulation of growth and increased supply of root respiratory substrates (Cruz *et al*., 1993). Elevated $CO_2$ decreased foliar N and P concentration in groundnut and blackgram under rainfed alfisol condition due to the higher biomass production and dilution effect. Crop specific responses of N uptake kinetics is one of the potential mechanisms by which elevated $CO_2$ might affect competitive balance among co-existing crops, thereby affecting ecosystem productivity and composition.

#### 4.1.2 *Moisture Stress*

- Water dependent diffusion and mass flow of nutrients to the roots slows with increasing soil moisture deficit as depicted in Fig. 5.
- Impaired root growth under deficient moisture condition decreases the capture of immobile or less mobile nutrients such as phosphorus and zinc.

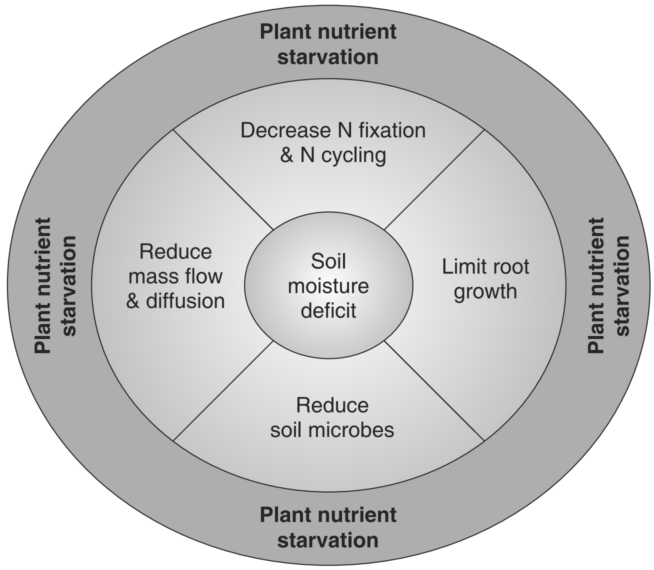


**Fig. 5** Impact of soil moisture stress on plant nutrition

- Drought inhibits N-fixation in legume crops and interrupts N cycling by hindering the soil bacterial activity.
- Root-mycorrhizae symbiosis is not overly sensitive to moderate soil moisture deficits.
- Part of the benefit provided by mycorrhizae under drought conditions is associated with increase in nutrient transfer to the roots.

### *4.1.3 Excessive Moisture*

Impact of flooding on nutrient availability and its use efficiency was illustrated in Fig. 6.

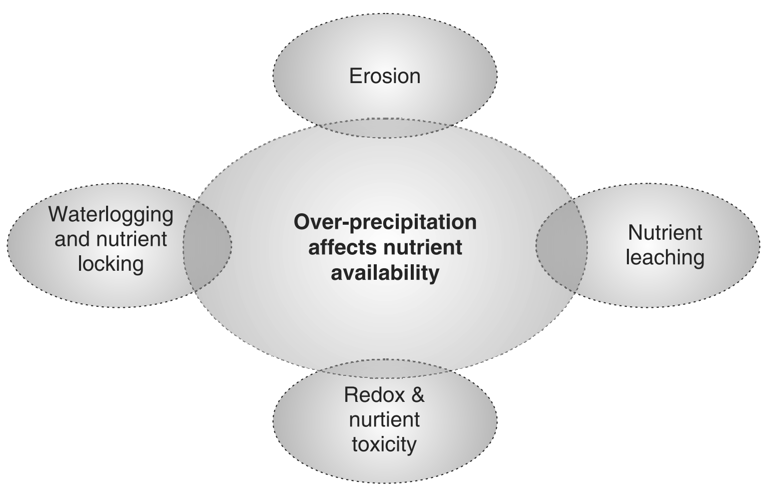


**Fig. 6** Impact of flooding on plant nutrition

- High intensity rainfall events accelerate the erosion leading to loss of nutrient rich top soil and surface applied fertilizers.
- Fastened the nitrate leaching process.
- Waterlogged soils become hypoxic.
- Oxygen dependent active transport of nutrients get slowdown and impaired the plant growth.
- Change in soil redox status can lead to Mn, Fe and Al toxicity.
- Under oxygen limited situation, nitrate is used as alternative electron acceptor, which may lead to N losses through denitrification.

### 4.1.4 Soil Temperature

Many studies have demonstrated that changes in soil temperature can directly affect plant nutrient acquisition by changing root transport properties for $NH_4^+$, $NO_3^-$, $PO_4^{3-}$ and $K^+$. Soil temperature might alter nutrient uptake capacity and it is largely determined by the degree to which growth and root shoot ratio is affected. If changes in soil temperature lead to an increased root-absorbing surface relative to shoot size, then there will be a down-regulation of ion influx. On the other hand, if changes in soil temperature lead to a relative increase in shoot versus root size, then ion uptake is likely to increase per unit root.

Soil temperature has marked effects on root characteristics such as growth, morphology, longevity, respiration and membrane fluidity, which influence plant nutrient acquisition efficiency (Bassiri Rad, 2000). However, some research evidence showed no interactive effect of elevated $CO_2$ and temperature on P and N acquisition (Bassiri Rad *et al*., 1996). Higher temperature does not modulate the nutrient dilution effect often observed in plants exposed to elevated $CO_2$. Temperature increases lead to higher respiration rates, shorter periods of seed formation, which in turn lowers biomass production. Impacts of temperature on ecosystems cannot be understood without taking nutrient cycling into account. Meta-analysis of soil warming experimental results showed significant positive effects on N mineralization and plant productivity (Rustad *et al.,* 2001). According to Kerkhoff *et al*. (2005) the actual net primary productivity is invariant with temperature and argues that nutrient feedbacks offset temperature effects on kinetics of photosynthesis and respiration. Modelling studies also demonstrated the importance of nutrient cycling in modulating ecosystem response to temperature. Nutrient cycling is strongly affected by precipitation and soil moisture availability (Austin and Vitousek, 1998).

### 4.1.5 Soil Salinity

Salinity affects the mineral nutrient uptake in plants through its effect on nutrient availability, transport, partitioning in plants and ionic imbalance due to the competition of nutrients such as $K^+$, $Ca^{2+}$ and $NO_3^-$ with the toxic ions $Na^+$ and $Cl^-$. Mineral nutrients play a vital role in determining plant resistance to salinity (Yuncai and Schmidhalter, 2005). Because it causes a similar effect on plant growth and development through a water deficit or soil moisture stress condition, potassium is equally important to maintain the turgor pressure of the plant under salinity stress. Calcium is a key signal messenger for regulating plant resistance to salinity as that of K. High $K^+ : Na^+$ ratios will also improve the resistance of the plant to salinity. The competition between $Cl^-$ and $NO_3^-$ under saline conditions means that the form of N plays a critical role in determining the growth of salinized plants. Compared to primary and secondary nutrients, micronutrients might be less important with respect to plant resistance to salinity.

## 4.2 Biotic Factors Affecting Nutrient Use Efficiency

### 4.2.1 Soil Biology

Soil fauna play a vital role in maintaining nutrient availability to crop plants. Directly below ground herbivory that can reduce fine root absorbing surface area or facilitation of root growth through earthworm channels. Indirectly, it improves the soil physical properties, nutrient transformation, population level interactions with microflora and the comminution and digestion of litter. Experimental evidence indicates that nutrient mineralization increases significantly in soil systems containing soil fauna, compared to those devoid of fauna (Carcamo *et al*., 2001). In their association with their host plant rizhobacteria may differently colonize their host plant. They may colonize the rhizosphere, the root surface or the intercellular spaces of the host plant. The colonizing ability of rizhobacteria is determined by utilizing organic acids rather than sugars, their chemotaxis response, mobility and production of lypopolysaccharides and proteins (Lugtenberg and Bloemberg, 2004). Microbial respiration and the mineralization of N and sulphur increase over the range of temperatures in different soils. Lipson *et al*. (2000) demonstrated that winter increases microbial biomass in dry alpine meadows were followed by spring declines related to a sustained increase in soil temperature and a corresponding decrease in soluble organic carbon.

### 4.2.2 Root Morphology

Soil physical and chemical parameters control the soil nutrient concentrations and movement into the root system, besides soil temperature also influences nutrient uptake through direct effects on the growth and physiology of plant root systems. The amount and duration of root growth, root morphology and root spatial distributions can be affected by soil temperature. Crop plants uptake the ions such as iron, $NH_4^+$, $NO_3^-$ appears to occur at higher rates near the apical portions of roots, while uptake of $K^+$ occurs at equal rates along the root (Clarkson, 1996). Such variation in ion uptake with root age may have important implications for plant nutrition if the average longevity of populations of fine roots is altered by environmental conditions.

### 4.2.3 Root Physiology

Changes in soil temperature directly affect root physiology in several ways in combination with soil-mediated controls on nutrient availability (diffusion, mass flow and mineralization) and nutrient uptake.The influx of nutrients into living cells of roots occurs by transport across the plasma lemma through high and low affinity transporter proteins that operate at low and high concentrations, respectively and are thought to be more or less specific to each ionic species (BassiriRad, 2000). In his earlier work he demonstrated that $PO_4^{3-}$ uptake by *Eriophorum vaginatum* increased as soil temperature rose from 5 to 15°C, but decreased with further increases in temperature. In addition, other factors such as plant demand for nutrients, root system, surface area and previous N nutrition are known to modify the response of nutrient uptake to changes in soil temperature. Root respiration is known to increase with rising soil temperature (Atkin *et al*., 2000) due to higher availability of carbohydrates from enhanced photosynthesis, providing more energy for active transport. Higher rates of root respiration result in higher concentrations of $CO_2$ in soil solution of which the dissociation products $H^+$ and $HCO_3^-$, promote ion exchange reactions at the surface of clay and humus particles, freeing nutrient ions for uptake (Larcher, 1995). Formation of carbonic acid as a result of increased respiration can decrease rhizosphere soil pH, which is widely known to affect the availability and uptake of essential ions, especially micronutrients (Marschner, 1995). The effect of enhanced root and microbial respiration on soil solution chemistry and plant nutrition is determined to a large extent by the buffering capacity of the soil. Properties of cell membranes also change with soil temperature, affecting nutrient uptake. There is a decrease in water uptake at low soil temperatures, caused primarily by increased resistance to water movement within the root due to higher viscosity of water and reduced permeability of cell membranes (Wan *et al*., 2001). The climatic variables such as excess moisture, moisture stress, and high $CO_2$ and soil temperature were highly influence the plant metabolitic function, nutrient availability and uptake mechanisms (Clair and Lynch, 2010). Different climate change variables and their interaction on mineral nutrient availability is given in Table 2.

**Table 2** Impact of weather variables on plant nutrient availability

| *Weather variables* | *Influence on plant metabolism and nutrient availability* |
|---|---|
| Excessive moisture (flood, storm, heavy rainfall) | Nutrient leaching, removal of fertile clay and loss of surface nutrients and organic carbon by the erosion process |
| Deficient moisture (monsoon failure, elevated temperature) | Excessive evapotranspiration altered mass flow of nutrients to roots theirby affect the availability of $NO_3$, $SO_4$,Ca, Mg and Si |
| High soil temperature and $CO_2$ | Water tension changes and influences the root absorption. Increased/ decreased root activities, which affect the availability of all nutrients, especially P and Zn |
| High $CO_2$ | Root absorption and exudation process of soil microbes especially mycorrhiza, which enhances the availability of P and Zn |
| Moisture stress and high soil temperature | Alter the microbial diversity, which is directly responsible for biological N fixation and N cycling through symbiotic and non-symbiotic processes |
| Waterlogging /Flooding | Reduction and oxidation processes affect the nutrient availability mainly Mn, Fe, Al and B |
| High atmospheric temperature | Alter the plant physiological and metabolism, thereby affect the nutrient uptake from the soil |
| Excess precipitation and soil temperature | Enhances the solubility and capillary rise of salts from sub surface to surface, which lead to salinity |

Plants accumulate nutrients from the soil solution pool and nutrients must be in solution to be mobile in the soil. In the absence of roots, steady state solution phase concentrations of nutrient ions are controlled by adsorption-precipitation and desorption-dissolution reactions between nutrients and the surface complex of soil, mineralization and immobilization for solutes of organic origin and additions from fertilizer (Barber, 1995). The different processes and parameters controlling nutrient availability is given in Table 3. Biological transformation between organic and inorganic pools is strongly influenced by moisture and temperature and thus global climate change may strongly influence solution concentrations of N as well as S. Some studies proposed that soil C pool size will not change as increased soil respiration and decomposition caused by soil warming will be moderated by the increased C supply below ground (Kirschbaum, 2000). Increasing $CO_2$ may not exert a significant direct effect on N mineralization but associated warming increased N mineralization and leading to increased solution-phase N. Some studies have examined the impacts of elevated $CO_2$ on solution-phase K availability is not strongly controlled by biological activity. Rates of adsorption and desorption reactions will accelerate with increased temperature and changes in soil moisture may further modify reactions by altering the ionic strength of the soil solution. However, uncertainties surrounding the magnitude of temperature increases coupled with the spatial and temporal variation in soil moisture make it challenging to predict how climate change will impact plant nutrient availability.

**Table 3** Impact of climate change on soil and plant factors controlling nutrient availability

| *Nutrient acquisition governing factors* | *Soil and plant process controlling nutrient availability* | *Impact climate change variables on nutrient use* |
|---|---|---|
| Concentration of nutrients in soil solution | Excess moisture, drought, temperature, organic matter and microbial activity; kind, time, rate and placement of fertilizer influence mineralization and immobilization process in the nutrient cycle. Type of clay minerals, buffering capacity, temperature, pH, soil moisture and ionic strength control the adsorption or desorption of applied nutrients in the soil. | Increasing soil temperature has positive and negative impact on soil and plant process controlling nutrient availability; atmospheric rise of $CO_2$ enhances fine root growth and exudates alter buffering capacity of the soil.<br>Excess or deficit of soil moisture boost or slow down the nutrient availability and uptake processes. Increased temperature and excess soil moisture will fasten the volatilization of surface applied N fertilizers and leaching losses of nutrients. |
| Nutrient transport /movement | Mass flow or diffusion of nutrients from the solution phase to plants mainly depend on the soil moisture, temperature, bulk density, hydraulic conductivity of soil, soil solution concentration, water movement and plant nutrient uptake potential. | Atmospheric rise of $CO_2$ reduces transpiration rate, which in turn suppres nutrient movement to root system but it increases root exudation and fine root growth, thereby enhancing buffering capacity, ionic concentration in solution and nutrient movement through diffusion. Excess moisture or drought may improve or slow down the nutrient movement by mass flow and diffusion process. |
| Plant nutrient uptake | Root morphological traits such as length, diameter, surface area, branching, spatial distribution and root hairs, ionic concentration and nature of ion present in the solution phase influence the nutrient availability and uptake kinetics. | Atmospheric rise of $CO_2$ and temperature will increase fine root and root surface area development respectively. Excess or soil moisture stress may increase or depress the nutrient movement by counteracting mass flow or diffusion process. |

### 4.3 Fertilizer Management

Best fertilizer management strategies are based on the '4 R' principle of right source, at the right rate, at the right time and at right placement to improve the nutrient use efficiency of crops, thereby reducing fertilizer requirement and associated GHGs emissions. Managing nitrogen fertilizer levels is challenging because appropriate application rates will differ for each agro ecosystem and growing season. Fertilizer applications that are carefully timed to maximize crop uptake, reduce application rates and $N_2O$ emissions without decreasing crop yield. Fertilizer placement is mainly based on the nature and type of fertilizer and crops grown. By managing the 4 Rs principle properly, we can able to achieve higher nutrient use efficiency with sustainable crop yield and environmental quality.

## 5. MANAGEMENT STRATEGIES FOR ENHANCING NUTRIENT USE EFFICIENCY

### 5.1 Adoption of Resource Conserving Technologies

Avoiding excessive fertilizer applications to cropland can reduce farmers' operating costs. A number of resource conserving practices and technologies are available to increase the efficiency of fertilizer use and reduce $N_2O$ emissions.

The ways and means are matching the supply of fertilizer to the demands of specific crops, ensuring the appropriate timing of nutrient applications, using efficient irrigation practices, converting to nitrogen-fixing plants as cover crops in the crop rotation and employing advanced fertilization techniques such as controlled-release fertilizers and nitrification inhibitors, which slow the conversion of ammonium to nitrate nitrogen.

- Conservation agriculture practices involving zero or minimum-tillage with direct seeding, permanent or semi-permanent residue cover and crop rotations have potential to increase soil organic matter, enhance input use efficiency, minimize the GHG emission and improve soil health.
- Minimum tillage and residue mulching maintain the favourable microclimate in the soil thereby enhance the nutrient use efficiency and minimize the greenhouse gas emission.
- Reducing the intensity and frequency of disturbance will help to protect soil carbon sinks. Practising reduced cultivation techniques where appropriate or moving towards plough sole or seeding zone of the soils.
- Site-specific measures of no-till farming, terracing or buffer strips for preventing run-off and erosion losses of P, N and other nutrients.
- The rotation of crops is not only necessary to offer a diverse source to the soil micro-organisms, but their root at different soil depths and are capable of exploring different soil layers for nutrients. Nutrients that have been leached to deeper layers and that are no longer available for the commercial crop can be reutilized by the crops in rotation.
- Practising suitable cover crop concept for protecting the soil from degradation.
- Designing the seeds using suitable bio-inoculants such as azospirillum for cereals, rhizobium for legumes, acetobacter for sugarcane and phosphobacteria for all the crops. It stimulates the germination and growth by production of growth promoting substance like vitamin-B complex, indoleacetic acid and gibberellic acids.

- Band placement of P and K fertilizer in no-till systems to improve nutrient availability during early growth phase.
- Band placement of fluid P fertilizer on calcareous soils overcomes the P fixation capacity and enhances the P use efficiency.
- Need based K application is essential to replenish declining indigenous K supply from minerals and irrigation and maintain the mobilizing non-exchangeable K in the clay minerals.
- Splitting of K applications to minimize leaching, increase stalk strength and resistance to diseases and improve the quality of harvested produce.
- Site-specific management of spatial variability in soil supply and crop removal through variable-rate application of P or K.
- Controlled release of nutrition is recommended on light soils, in rainy areas, where mid-season application is not feasible or where nitrogen application is restricted.
- Foliar feeding can provide the nutrients needed for normal development of crops in cases where absorption of nutrients from the soil is disturbed. As the uptake of nutrients through the foliage is considerably faster than through roots. Foliar sprays are also one of the proven methods of prompt correction of nutrient deficiencies and application of nutrients through foliar nutrition during critical growth stages dramatically increases yields and improve crop quality.
- Fertigation technique enables growers to maximize the use of water resources and increase the efficiency of fertilizer. This technique is particularly appropriate for high value crops under arid and semi-arid conditions. It involves the addition of soluble fertilizers into irrigation systems, preferably using a drip system which allows uniform water distribution and feeding of the crop. The fertilizer can be applied to the crop whenever it is needed at active root site of the plants.

## 5.2 Climate Smart Soil Management Practices

Good soil management can help to achieve maximum nutrient efficiency and sometimes it regulates emissions of three key greenhouse gases *viz*., carbon dioxide, methane and nitrous oxide from agriculture. The science behind the role of soil and fertilizer management in reducing greenhouse gas emissions is still relatively young and the relationship between carbon and nitrogen in the soil is complex. More understanding is needed to fine-tune practices further. Following existing features of good soil management practice is generally still advantageous due to the wider production and environmental benefits gained in the climate changing era.

- Reducing compaction will improve nutrient uptake in the soil and help to reduce the release of nitrous oxide.
- The most efficient management practice to reduce nitrous oxide emission is site-specific nutrient management. The emission could also be reduced by usage of nitrification inhibitors such as nitrapyrin and dicyandiamide. There are some plant derived organics such as neem oil, neem cake and karanj seed extract which can also act as nitrification inhibitors, which also reduce $CH_4$ emissions from fertilized rice fields.

- Efficient nitrogen management can reduce nitrous oxide emissions by meeting crop requirements and minimizing residual nitrogen. Use recognized nutrient management plan and follow soil test based fertilizer recommendations.
- Application of organic enriched P and Zn application especially pulse and oilseed crops improved the crop yield and also enhance the nutrient use efficiency.
- Optimum potassium application is recommended in K deficit soil to maximize other nutrient efficiency, especially nitrogen.
- Soil application of sulphur is advocated especially pulses and oilseeds growing areas and sulphur deficient soil to combat climate change.
- Site specific multi-micronutrient mixture application is advocated to alleviate soil micronutrient deficiency and enhance the crop yield under varying climate.
- Soil application of azosprillum, rhizobium and acetobacter is recommended for cerelas, pulses and sugarcane crop respectively and phosphobacteria application is common for all the crops.
- Biofertilizers will be enriched with 200 kg of compost or organic manure and kept overnight. Enriched biofertilizer is incorporated in the soil at the time of sowing or planting to enhance the nutrient use efficiency.
- Crop specific bio-fertilizers application are known to play a number of vital roles in soil fertility, crop productivity and production in agriculture as they are ecofriendly and cannot substitute for inorganic fertilizers. These are ecofriendly, low cost inputs, which can be used by small and marginal farmers to reduce their chemical fertilizer cost and to sustain the soil health and crop yield.
- Application of biochar with soil test based balanced fertilizer enhanced the fertilizer use efficiency and reduced the prime greenhouse gas emission.
- Application of biochar with biofertilizer enabling the carbon sequestration and reduce greenhouse gases emission with high input use efficiency.
- Practising crop and soil based integrated application organic, inorganic and biofertilizer enhancing the crop yield and sustain the soil health.
- Carbon storage in soils undermost forms of agricultural management is limited, but farmers can potentially improve and maintain organic matter in soils by regular addition of crop residues and manures such as compost and digestate.
- Precise fertilizer application based on the remote sensing and GIS platforms through soil variability map and variable rate applicator techniques. Precision farming systems are already available to ensure farmers can draw up careful plans and the most advanced systems can reduce fertilizer usage by about one-third. For small scale farmers in the developing world, who have no access to modern farming equipment, the best solution for improving fertilizer practices is to increase access to independent advice from local experts such as research institutes.

**Nutrient management strategies to combat climate change**

- Appraise the nutrient status of the farm using standard soil testing method and prepare the fertility rating chart and categorize the deficient nutrient.

- Assess the different nutrient resources potential available to the farmers.
- An assessment of how best to fill the gap between requirement and availability through decision supporting system.
- Balanced fertilizer recommendation should be made by integrating soil test value, crop requirement and available nutrient resource by using decision supporting systems.

***(i) The principles of sound fertilizer management***

The basic principle behind the best fertilizer management practices is simple and given in the Fig. 7, that is the 4R using the right source, at the right rate, right time and right place which implies that how fertilizer applications can be managed to achieve economically feasible, socially acceptable and environmentally sustainable crop production.

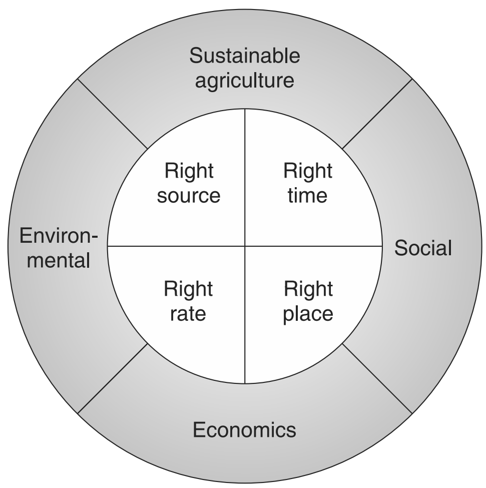


**Fig. 7** Principles of fertilizer management and its impact

According to the Roberts (2006) the following are guiding principles for fertilizer management.

**Right source:** Match the fertilizer source and product to crop need and soil properties. Be aware of nutrient interactions and balance nitrogen, phosphorus, potassium and other nutrients according to soil analysis and crop needs. Balanced fertilization is one of the keys to increasing nutrient use efficiency.

**Right rate:** Match the amount of fertilizer applied to the crop needs. Too much fertilizer leads to leaching and other losses to the environment and too little results in lower yields and crop quality and less residue to protect and build the soil. Realistic yield goals, soil testing, omission plots, crop nutrient budgets, tissue testing, plant analysis, applicator calibration, variable rate technology, crop scouting, record keeping and nutrient management planning are the best management practices that will help determine the right rate of fertilizer to apply.

**Right time:** Make nutrients available when the crop needs them. Nutrients are used most efficiently when their availability is synchronized with crop demand. Application timing (pre-plant or split applications), controlled release technologies, stabilizers, inhibitors and product choice are examples of best management practices that influence the timing of nutrient availability. Advanced tools such as SPAD meter and leaf colour chart to be used to meet out the crop demands at right time.

**Right place:** Place and keep nutrients where crops can use them. Application method is critical for efficient fertilizer use. Crop, cropping system and soil properties dictate the most appropriate method of application, but incorporation is usually the best option to keep nutrients in place and increase their efficiency. Conservation tillage, buffer strips, cover crops and irrigation management are other best management practices that will help keep fertilizer nutrients where they were placed and accessible to growing crops.

***(ii) Ways to foster improved nitrogen use efficiency by manufacturer*** **(IFA, 2007):**

- Develop and promote fertilizer recommendations that balance soil nutrient supply and mineral fertilizer applications with actual crop needs
- Develop products with improved physical characteristics
- Develop products with chemical compositions that meet the variable nutrient requirements of crops and improve use efficiency
- Make a wide range of smart fertilizer products available to farmers
- Develop and promote nutrient/fertilizer best management practices
- Measure the performance of the recommended products and practices

## 5.3 Breeding for Nutrient Use Efficiency

### *5.3.1 Exploiting Genetic Potential to Enhance Nutrient Use Efficiency*

Nutrient efficient genotypes are adapted to environments with low nutrient availability. It is useful to screen and exploit the genetic variability present across crop species to enhance nutrient use efficiency. The nutrient use efficiency of the genotypes should be looked into two angles, namely, ability of the plant to extract the nutrient from soil (uptake) and ability of the plant to convert intake nutrients into grain yield (utilization efficiency). These parameters can be measured by nutrient use efficiency and utilization efficiency as given by Ortiz-Monasterio (2001). To satisfy site and management specific needs under changing climatic situation, the genotypes to be evaluated in high and low nutrient status environment and group them for low and high input responder. Simultaneous selection for both nutrient use efficiency and tolerance to nutritional stress is possible if the mechanisms that confer efficiency and tolerance are not competitive (Fritsche-Neto and DoVale, 2012).

Nutrient-efficient genotypes may have an increased capacity (i) to exploit the soil (large root surface area), (ii) to convert non-available nutrient forms into plant available forms and (iii) to take up nutrients across the plasma membrane (Rengel, 2001). Plant species increase their capacity to access nutrients by altering root morphology and by changing the capacity and affinity of plasma membrane-embedded transporters capable of carrying nutrients into the cytosol (Rengel and Marschner, 2005).

The existence of genetic variability had been reported for the nutrient use efficiency (NUE) of cultivars. The efficient use of nutrient is the cumulative effect of following efficiencies that varies with genotypes to genotypes within crop species.

*(a) Uptake efficiency:* It depends on acquiring the nutrients from soil, entry rate into roots and radial transport into roots and all are based on root traits.

*(b) Incorporate efficiency:* Transport of nutrients to shoots and leaves are based on shoot parameters.

*(c) Utilization efficiency:* Based on remobilization, i.e., utilisation absorbed nutrients to produce biomass (Baligar *et al*., 2001).

The environment factors like solar radiation, temperature and soil moisture also influence the NUE in plant. Hence, in the changing climate situation it is essential to opt balance between the stress adapted genotypes and NUE to sustain the crop yield.

The plant species and cultivars within species differ in uptake and utilization of nutrients. It is mainly attributed to morphological, physiological and biochemical processes in plant and its soil, nutrients, biological and management practices (Baligar *et al*., 2001). Hence, the NUE improved by the manipulation of plants, soil, fertilizer, biological, environment factors and ideal management practices.

The crop improvement approaches are used to increase nutrient use efficiency (NUE) in crop plants are traditional breeding, marker-assisted selection, targeted breeding through pyramiding and by gene transfer and manipulation (Good *et al*., 2004; Rengel and Marschner, 2005). The prospects for genetically manipulated plants to enhance nutrient availability under given environmental conditions can be strengthened by (i) understanding the regulation of the exudation process, (ii) elucidating the regulation of root morphology, (iii) characterizing the synthesis and activity of membrane-embedded nutrient transporters, and (iv) understanding the interactions among root exudation, indigenous rhizosphere microorganisms and nutrient availability (Rengel and Marschner, 2005).

### 5.3.2 Exploiting Variability of Micronutrients

In climate smart management practices, it is important to incorporate crop and edaphic factor specific micronutrient management. The efficient and sustainable strategy is to develop micronutrient efficient plant genotypes that can tolerate low nutrient supply may increase productivity on low fertility soils and reduce the fertilizer requirements (Khoshgoftarmanesh *et al*., 2010). To increase the micronutrients in edible portion of food crops, it is essential to identify the micronutrient responsive cultivars. The reports prove that there are inherent genetic variability is available in crop species in utilizing micronutrients. Screening for micronutrient responsive genotypes and exploring the available genetic variability in crop improvement programme are vital to the present situation.

## 6. FUTURE CHALLENGES AND THREATS

- A key priority for future research is to determine whether there will be a sustained increase in nutrient availability due to global warming and how this will affect productivity.
- Till date, experimentation on crop plants has not found conclusive evidence that physiological efficiency is altered in high $CO_2$ environments.
- Further research could clarify the best fertilizer additions under specific circumstances and develop new nitrogen related products and smart delivery mechanisms that are driven by factors related to temperature, water and host plant.

- Better understanding of the relationship between $N_2O$ emissions and extreme weather events may also become increasingly important to enhance nutrient use efficiency under changing climate.
- Crop specific fertigation through water soluble fertilizer and its use efficiency under changing climate to be studied in different agro-ecological zone
- The nanotechnology promises slow release fertilizers (nanoporous zeolites) and soil quality and plant health monitoring systems (nanosensors). The new products and tools would go a long way in managing soil fertility and enhancing crop productivity.
- Greater research and development efforts are required to increase shelf-life of biofertilizers by way of isolating location-specific strains, better production technology avoiding contamination and better storage and handling.
- The liquid cultures containing cell protectants maintain high microbial numbers and promote formation of resting cells like cysts and spores having resistance to abiotic stresses.
- Dynamics and response of secondary and micronutrient under elevated $CO_2$ may be explored in detail under field condition.
- Adaptation to climate change requires multidisciplinary solutions that include the development of appropriate nutrient efficient cultivars and mechanisms to facilitate farmers' access to the cultivars.
- Varieties with increased resilience to abiotic and biotic stresses will play an important role in autonomous adaptation to climate change.
- Identify the candidate genes and nutrient uptake efficient traits valuable for breeding and incorporate these into elite cultivars and to evaluate their performance under real agricultural field conditions under changing climate.

## 7. CONCLUSION

Climate smart agricultural technologies are available to increase the efficiency of fertilizer use and reduce $N_2O$ emissions. The ways and means are synchronizing the supply of fertilizer to the demands of specific crops, ensuring the appropriate timing of nutrient applications, using efficient irrigation practices, converting to nitrogen-fixing plants as cover crops and crop rotation. Practising advanced fertilization techniques such as controlled release fertilizers, urease inhibitors and nitrification inhibitors, which slow the conversion of ammonium to nitrate nitrogen. Biofertilizer helps in increasing crop productivity by way of increased biological nitrogen fixation, phosphorus solubilization and mobilization, increased availability or uptake of nutrients through solubilization or increased absorption stimulation of plant growth through hormonal action or antibiosis or by decomposition of organic residues. In addition, biofertilizer replaces part of chemical fertilizers, reduces amount and cost of chemical fertilizers, thus prevents the environmental pollution from excess application of chemical fertilizers.

In the context of global environmental changes and other constraints to increase yield further, the efficient use of nutrient, especially N and water have emerged as two key targets. Complementary to bridging the yield gap, tailoring of cultivars with high nutrient use efficiency and yield with abiotic tolerance is required to cope up the climatic variability. Adoption of climate smart soil and crop management technologies and improved cultivars must be explored in future to combat the climate change and sustain the livelihood security of the farming community.

## References

Afzal, A., and Bano, A. (2008). Rhizobium and phosphate solubilizing bacteria improve the yield and phosphorus uptake in wheat (*Triticum aestivum* L*.). Int. J. Agri. Biol.* 10: 85-88.

Atkin, O.K., Edwards, E.J., and Loveys, B.R. (2000). Response of root respiration to changes in temperature and its relevance to global warming. *New Phytologist.* 147: 141-154.

Austin, A.T., and Vitousek, P.M. (1998).Nutrient dynamics on a precipitation gradient in Hawaii.*Oecologia* 113: 519-529.

Baligar, V.C., Fageria, N.K., and He, Z.L. (2001) .Nutrient use efficiency in plants, *Commun. Soil Sci. Plant Anal*. 32(7&8): 921-950.

Barber, S.A. (1995). Soil Nutrient Bioavailability: a Mechanistic Approach, second ed. JohnWiley & Sons Inc., New York, USA. pp. 414.

BassiriRad, H., Thomas, R.B., Reynolds, J.F., and Strain, B.R. (1996). Differential responses of root uptake kinetics of $NH_4^+$ and $NO_3^-$ to enriched atmospheric $CO_2$ in field grown loblolly pine. *Plant, Cell and Environment.*19: 367-371.

Bassirirad, H. (2000). Kinetics of nutrient uptake by roots: responses to global change. *New Phytol*.147: 155-169.

Biswas, P.P., and Sharma, P.D. (2008). A new Approach for estimating fertilizer response ratio: the Indian scenario, *Indian J. Fert*. 4(7): 59-62.

Brennan, R.F., and Bolland, M.D.A. (2009). Comparing the nitrogen and potassium requirements of canola and wheat for yield and grain quality. *J. Plant Nutr.* 32(12): 2008-2026.

Carcamo, H.A., Prescott, C.E., Chanway, C.P., and Abe, T.A. (2001). Do soil fauna increase rates of litter breakdown and nitrogen release in forests of British Columbia,Canada.*Can J For Res.* 31: 1195-1204.

Clair, St., and Lynch, Jonathan, P. (2010). The opening of Pandora's Box: climate change impacts on soil fertility and crop nutrition in developing countries. *Plant Soil.* 335: 101-115.

Clarkson, D.T. (1996). Root structure and sites of ion uptake. In: Waisel, Y., Eshel, A., Kafkafi, U .(eds) *Plant roots: the hidden half*, 2nd edn. Marcel Dekker, New York. pp. 483-510.

Cruz, C., Lips, S.H., and Martins-Loucao, M.A. (1993). The effect of nitrogen source on photosynthesis of carob at high $CO_2$ concentrations. *Physiologia Plantarum.* 89: 552-556.

Dobermann, A., and Cassman, K.G. (2005). Cereal area and nitrogen use efficiency are drivers of future nitrogen fertilizer consumption. *Science in China Ser. C Life Scienc*es. 48: 745-758.

Dobermann, A. (2007). Nutrient use efficiency measurement and management.IFA International Workshop on Fertilizer Best Management Practices, Brussels, Belgium, First edition, IFA, Paris, France. pp. 1-28.

DeLuca, T.H., MacKenzie, M.D., Gundale, M.J., and Holben, W.E. (2006). Wildfire-produced charcoal directly influences nitrogen cycling in ponderosa pine forests. *Soil Sci Soc Am J.* 70: 448-453.

Duxbury, J.M., Bouldin, D.R., Terry, R., and Tate, R.L.(1982).Emissions of nitrous oxide from soils. *Nature.* 298: 462-464.

El-Komy, H.M.A. (2005). Co-immobilization of *A. lipoferum* and *B. megaterium* for plant nutrition. *Food Technol Biotech*. 43(1): 19-27.

Fangmeier, A., Gruters, U., Hogy, P., Vermehren B., and Jager, H.J. (1997). Effects of elevated $CO_2$, nitrogen supply and tropospheric ozone on spring wheat-II.Nutrients (N, P, K, S, Ca, Mg, Fe, Mn, Zn). *Environ. Pollut*. 96(1): 43-59.

Flynn,C. Helen . (2009). The Role of Nutrient Management in Mitigation. Focus 16 brief 7 of May 2009. www.ifpri.org.

Fritsche-Neto, R., and DoVale, J.C. (2012). Breeding for Stress tolerance or resource-use efficiency. In: R. Fritsche-Neto and A. Borém (eds.), Plant Breeding for Abiotic Stress Tolerance, Springer-Verlag Berlin Heidelberg. pp. 13.

Good, A.G., Shrawat, A.K., and Muench, D.G. (2004). Can less yield more? Is reducing nutrient input into the environment compatible with maintaining crop production? *Trends in Plant Science*. 9(12): 597-605.

Guo, J.H., Liu, X.J., Zhang, Y., Shen, J.L., Han, W.X., Zhang, W.F., Christie, P., Goulding, K.W.T., Vitousek, P.M., and Zhang, F.S. (2010). Significant acidification in major Chinese croplands.*Science*. 327: 1008-1010.

Gupta, A.K. (2004). The complete technology book on biofertilizers and organic farming.National Institute of Industrial Research Press. India. pp. 168.

IPCC- Inter-Governmental Panel on Climate Change (2007). Climate change 2007: The physical science Basis, Summary for Policy makers.

IFA- International Fertilizer Association. (2007). Fertilizer Best Management Practices: General Principles, Strategy for their Adoption and Voluntary Initiatives vs. Regulations." Proceedings of the International Workshop on Best Fertilizer Management Practices, Brussels, Belgium, 7-9 March.IFA, Paris, France.

IFA - International Fertilizer Association. (2011). Global fertilizer trade map.www.icis.com/fertilizer.

Johnston, A.E., Poulton, P.R., and Coleman, K. (2009). Soil organic matter: its importance in sustainable agriculture and carbon dioxide fluxes. In: D.L. Sparks (Editor), *Advances in Agronomy*, *Vol 101*. Elsevier Academic Press Inc, San Diego, pp. 1-57.

Kannan, P., Balasubramaniyan, P., and Prabukumar, G. (2011). Effect of different nutrient management practices on soil health indicators in groundnut system. In Annual report-2011, Dryland Agricultural Research Station, Chettinad, Tamil Nadu Agricultural University, Coimbatore.pp. 20-23.

Kerkhoff, A.J., Enquist, B.J., Elser, J.J., and Fagan, W.F. (2005) Plant allometry, stoichiometry and the temperature-dependence of primary productivity. *Global Ecology and Biogeography.* 14: 585-598.

Khan, K. S., and Joergensen, R. G.(2009). Changes in microbial biomass and P fractions in biogenic household waste compost amended with inorganic P fertilizers. *Bioresour. Technol*.100: 303-309.

Khoshgoftarmanesh, A.H., Schulin, R., Chaney, R.L., Daneshbakhsh, B., and Afyuni, M. (2010). Micronutrient-efficient genotypes for crop yield and nutritional quality in sustainable agriculture: A review. *Agronomy for Sustainable Development.* 30: 83-107.

Kirschbaum, M.U.F. (2000). Will changes in soil organic carbon act as a positive or negative feedback in global warming. *Biogeochemistry.* 48: 21-51.

Larcher, W. (1995). Plant physiological ecology. Springer, Berlin Heidelberg New York.

Lipson, D.A., Schmidt, S.K., and Monson, R.K. (2000). Carbon availability and temperature control the post-snow melt decline in alpine soil microbial biomass. *Soil BiolBiochem.* 32: 441-448.

Loladze, I. (2002). Rising atmospheric $CO_2$ and human nutrition: toward globally imbalanced plant stoichiometry. *Trends in Ecology & Evolution*. 17(10): 457-461.

Lugtenberg, B.J.J., and Bloemberg, G.V. (2004) .In *Pseudomonas* Vol. 1 ed. Ramos, J.L. Kluwer Academic Plenum Publishers, New York. pp. 403-430.

Manoj-Kumar, Swarup, A., Patra, A.K., Purakayastha, T.J., Manjaiah, K.M., and Rakshit, R. (2011). Elevated $CO_2$ and temperature effects on phosphorus dynamics in rhizosphere of wheat (*Triticumaestivum*L.) grown in a Typic Haplustept of subtropical India. *Agrochimica*. *55*: 14-31.

Marchner, H. (1995). Mineral Nutrition of Higher Plants.Academic, San Diego Samuel B.

Mehrvarz, S., Chaichi, M. R., and Alikhani, H. A. (2008).Effects of phosphate solubilizing microorganisms and phosphorus chemical fertilizer on yield and yield components of Barely (*Hordeum vulgare* L.). *J. Agric. & Environ. Sci.* 3: 822-828.

Mosier, A.R., Bronson, K.F., Freney, J.R., and Keerthisinghe, D.G. (1994).Use of nitrification inhibitors to reduce nitrous oxide emission from urea fertilized soils. *$CH_4$ and $N_2O$: Global Emissions and Controls from Rice Fields and other Agricultural and Industrial Sources,* (ed.K Minami, A Mosier and R Sass), Tsukuba: National Institute of Agro-Environmental Sciences.pp. 197-207.

Ortiz-Monasterio, J.I., Manske, G.G.B., and Ginkel, M.V. (2001).Nitrogen and phosphorus use efficiency, In *Application of Physiology in Wheat Breeding,* Reynolds, M.P., Ortiz-Monasterio, J.I. and McNab, A. (eds.), CIMMYT, Mexico.

Pregitzer, K.S., and King, J.S. (2005).Effects of Soil Temperature on Nutrient Uptake. Ecological Studies, Vol.181 Bassiri Rad, H. (Ed.) Nutrient Acquisition by Plants. An Ecological Perspective, Springer-Verlag Berlin Heidelberg.

Rengel, Z. (2001). Genotypic differences in micronutrient use efficiency in crops. *Communications in Soil Science and Plant Analysis.* 32: 1163-1186.

Rengel, Z., and Marschner, P. (2005). Nutrient availability and management in the rhizosphere: exploiting genotypic differences, *New Phytologist*. 168: 305-312.

Roberts, T.L. (2006). Improving nutrient use efficiency. In Proceedings of the IFA Agriculture Conference "Optimizing Resource Use Efficiency for Sustainable Intensification of Agriculture", 27 February - 2 March 2006, Kunming, China. International Fertilizer Industry Association (IFA), Paris, France.

Rustad, L.E., Campbell, J.L., Marion, G.M., Norby, R.J., Mitchell, M.J., Hartley, A.E., Cornelissen J.H.C., and Gurevitch, J. (2001).A meta-analysis of the response of soil respiration, net nitrogen mineralization, and above-ground plant growth to experimental ecosystem warming. *Oecologia.* 126: 543-562.

SamanSeneweera.(2011).Effects of elevated $CO_2$ on plant growth and nutrient partitioning of rice (*Oryza sativa* L.) at rapid tillering and physiological maturity. *Journal of Plant Interactions.* 6(1): 35-42.

Sardans, J., Penuelas, J., Prieto, P., and Estiarte, M. (2008). Drought and warming induced changes in P and K concentration and accumulation in plant biomass and soil in a Mediterranean shrubland. *Plant Soil*. 306: 261-271.

Seneweera, S. P., and Conroy, J.P. (1997).Growth, grain yield and quality of rice (*Oryza sativa* L.) in response to elevated $CO_2$ and phosphorus nutrition. *Soil Science and Plant Nutrition.* 43: 1131-1136.

Seufert, V., Ramankutty, N., and Foley, J.A. (2012). Comparing the yields of organic and conventional agriculture. *Nature*. 485(7397): 229-232.

Sharma, J.S., and P.D. Sharma.(2011). Food Security-Indian Scenario. In: Brar, M.S., and Mukhopadhyaya, S.S. (ed.) Potassium role and benefits in improving nutrient management for food production, quality and reduced environmental damages. Volume I IPI, *IPNI.* pp. 15-43.

Sturm, M., Schimel, J., Michaelson, G., and Welker, J.M. (2005). Winter biological processes could help convert Arctic tundra to shrubland. *BioScience.* 55: 17-26.

Tilman David, Kenneth, G., Cassman, Pamela A. Matson, Rosamond Naylor and Stephen Polasky.(2002). Agricultural sustainability and intensive production practices. *Nature.* 418: 671-677.

Van Noordwijk, M., Martikainen, P., Bottner, P., Cuevas, E., Rouland, C., and Dhillion, S.S. (1998).Global change and root function. *Global Change Biology.* 4: 759-772.

Wan, X., Zwiazek, J.J., Liffers, V.J., and Landhausser, S.M. (2001). Hydraulic conductance in aspen (*Populustremuloides*) seedlings exposed to low root temperatures. *Tree Physiol.* 21: 691-696.

Whitelaw, M. A. (2000). Growth promotion of plants inoculated with phosphate solubilizing fungi. *Adv. Agron*. 69: 99-151.

Wilts, A. R., Reicosky, D. C., Allmaras, R. R., and Clapp, C.E. (2004). Long term corn residue effects: Harvest alternatives, soil carbon turnover and root-derived carbon. *Soil Sci. Soc. Am. J.* 68: 1342-1351.

Yuncai, H.U. and Schmidhalter,U.R.S. (2005). Drought and salinity: A comparison of their effects on mineral nutrition of plants, *J. Plant Nutr. Soil Sci.* 168*:* 541-549.

Zaidi, A., and Khan, M. S. (2006). Co-inoculation effects of phosphate solubilizing microorganisms and *Glomus fasciculatum* on green gram – *Bradyrhizobium* symbiosis. *Turk. J. Agric*. 30: 223-230.