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Enhancing crop productivity through
soil and nutrient management

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The area under crops and cropping intensity are increasing day-by-day to feed ever growing man and animal population in arid zone. This trend can be continued for a long-time only by ensuring that plants had an adequate and balanced supply of nutrients and appropriate environments exist in soil for nutrients to be available to crop plants. Nutrient levels in arid soils are constrained by extremes of environments and can not meet the production requirements of today. External addition of nutrients in arid conditions pose economic burden and also carry risk. Two major approaches were discussed to achieve higher production levels with lower economic risks. First is the application of external inputs especially nitrogen (N) in optimum quantity with site specific management, and second is enhancing internal nutrients circulation by using crop residues and manure, cereal legume rotation, intercropping of legumes in cereals and mycorrhiza.

Key words: Crop productivity, Fertilizers, Nutrient management, Soil fertility

IN past 125 years India has experienced significant loss in area of grasslands/ shrub lands and forests and expansion of crop lands. Area under grasslands and forest decreased by about 20 and 26 million ha respectively whereas croplands increased by 48 million ha during this period. Of this 22 m ha area was added to crop lands from 1970s. Cropping intensity in the country was increased from 118 to 142% and ratio of gross irrigated area: cropped area was increased from 23 to 36.4%. These changes were not left even the deserts untouched. Cultivated area in Rajasthan has increased from 45 to 53% and during this period while cropping intensity increased from 110 to 128% and ratio of gross irrigated area: cropped area was increased from 15 to 24%. All this resulted in tremendous increase in production and productivity of different cereals, pulses and oilseeds in Rajasthan (Fig. 1). With 40% of the national production of mustard and pearl millet, and 80, 95, 98 and 65% of the national production of cluster bean, psylllium husk, henna and coriander Rajasthan ranks first in the nation and with 14% contribution towards pulses ranks second in the nation.

Major crops grown in different parts of Rajasthan were pearl millet, wheat, sorghum, maize, cotton, rapeseed and mustard, groundnut and horticultural crops. As per the cropping pattern in the State, the crop groups such as total cereals, oilseeds, pulses and fodder crops were accounted for about 42%, 21%, 18% and 15% of gross cropped area (GCA) respectively during the decade. Among the cereals, pearl millet (50.5%), wheat (27.9%), maize (10.5%) and sorghum (6.7%) were the major crops whereas rapeseed and mustard (45.4%), taramira (21.7%), soybean (14.0%), sesamum (10.0%) and groundnut (6.3%) were the major oilseeds grown in Rajasthan. Among total pulses, chick-pea, moth bean and moong bean, account for about 37.5, 33.5 and 22.1% respectively. In comparison to previous decade the share of total cereals declined drastically by 10% while the share of oilseeds increased by 6%. Share of pulses increased slightly from 17 % to little more than 18% per contra share of fodder crops was remained unchanged at around 15% of GCA. Among the cereals, the shares of pearl millet, wheat, maize and barley were increased but share of sorghum and small millets was decreased. Area under cotton was also declined.

Soil fertility under arid conditions, is constrained by environmental extremes of hot and cold temperatures, as well as by low water availability. With some exceptions, these soils have inherently low fertility. Nitrogen is generally deficient, availability of phosphorus is medium but potassium is generally adequate. Soils have low water-holding capacity, high pH, low soil organic matter (ranging from 0.1 to 0.5%). Shallowness, and stoniness at times are other specific problems. Thus, increasing requirement of food production can not be achieved by natural means alone and application of fertilizers is necessary (Fig. 1). But over a period we have learnt that even though external inputs increased

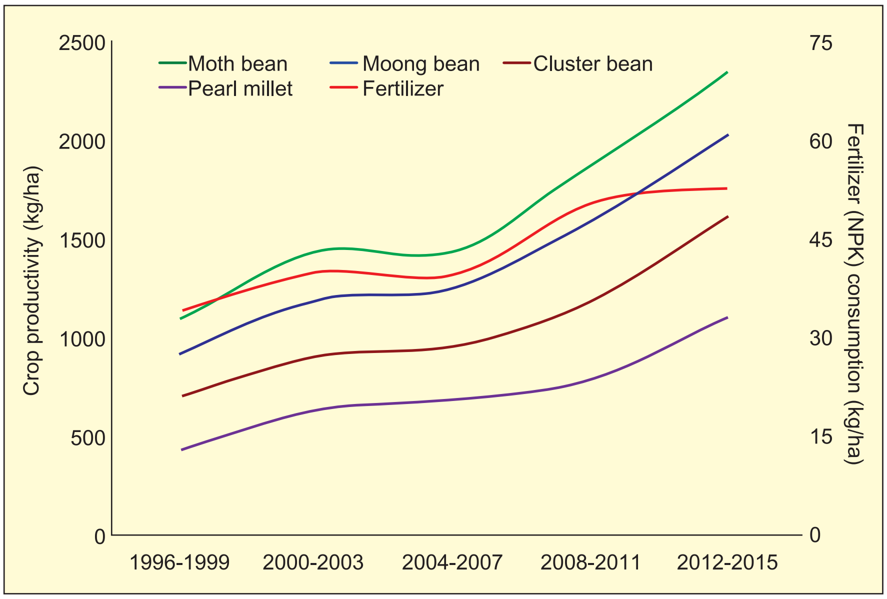

Fig. 1. Changes in pearl millet, moong bean, moth bean and cluster bean productivity and fertilizer consumption in last 20 years

productivity and contributed to sustainability of production, the use of fertilizers at so-called 'economic' levels, is usually prohibitively risky. It is unlikely that Indian arid lands can ever be competitive for grain production with the other states since arid areas generally have low overall production potential given their water and soil constraints. Further, given the poor access to markets and inadequate infrastructure in the region, low external-input technologies can be more impactful for sustainable production and livelihood improvement in arid region. A few important low input technologies and their impact are discussed here.

Guiding principles of nutrient management in arid soils

Nutrient use efficiency is evaluated using metrics that reflect crop uptake of fertilizer added in the current growing season. Low nutrient use efficiency is a consequence of temporal asynchrony and spatial separation between applied nutrients and the crop. As a result, efforts to improve nutrient utilization efficiencies emphasized on improved delivery of nutrients to the root zone during the period of crop uptake through modifications such as banding, fertigation, split fertilizer applications etc. As N is universally deficient in arid soils, major emphasis is given to N fertilizers. To increase crop access to N fertilizer, a variety of additives were developed that inhibit urease activity, nitrification and denitrification. These approaches were extremely successful in increasing nutrient use efficiency and maximizing yields; however, their utilization on mass-scale on small-farms met with limited success. Despite more than 30 years of concentrated effort, mass balances still indicated that annual N and P inputs consistently exceed harvested exports by 40 to >100% indicating substantial losses of these nutrients. This can be addressed by (*i*) application of fertilizers in optimum quantity, and (*ii*) internal circulation of nutrients.

Application of optimum quantity: Major quantity of N i.e. up to 70% of total N uptake, can be taken up by the pearl millet within first 30 days of growth. Though it slows down thereafter, but continues gradually till the grain filling stage. This high rate of N demand can not be met from the soil and thus pearl millet respond favourably to the N addition. Significant response to application of 40 to 80 kg N ha^{-1} was reported at CAZRI during the years of good rainfall. Comparison of different N-fertilizers showed that maximum yields were recorded with ammonium sulphate. But due to high cost of ammonium sulphate, urea became the major source of N in arid regions even though utilization efficiency of N from urea by pearl millet is very low. Various studies in CAZRI, Jodhpur revealed that the mixing of elemental S with urea or application of small quantity of ammonium sulphate before the application of urea increases its efficiency. NH_4 : NO_3 ratio in a N-fertilizer also effect its utilization efficiency and highest utilization efficiency from the applied N-fertilizer is recorded with 3:1 NH_4 : NO_3 ratio. One of the first step necessary for achieving higher fertilizer use efficiency is to apply the right amount of fertilizer. But the long-term estimations of N-requirement of crops under arid rain-fed conditions is difficult as the yield levels vary from zero- to three-fold of average yield. Using average yield in arid region is too conservative and may actually result in lowering average yields with time because of insufficient nutrient availability during favourable years. On contrary, use of relatively high yield goals results in excess N applications in most years which can greatly reduce profit. The current concern over the potential for excess N to degrade the environment also makes this alternative unacceptable. Thus in absence of exact requirements, application of nutrients at any rate leaves uncertainty. The cost of uncertainty is measured as the difference in N rate when soil N supply and crop N demand are unknown versus known perfectly. Eliminating uncertainty in soil N supply (but not crop demand) reduces average N rates by 5 to 40% in different crops while perfect knowledge of potential crop N demand (but not soil supply) reduces rates by 3 to 10%. Uncertainties in soil nitrogen supply can be reduced with site-specific N management approaches and choosing yield goals based upon (*i*) highest yield within the past 5 years with good crop management, (*ii*) yield goal set at 1.5 fold of long-term average, and (*iii*) yield goal based on soil capabilities as defined in Standard Soil Surveys, using yields of highest yield obtaining farmers' in the vicinity on the same kind of soil. This approach is very different from most extension services in India which provide a single, standard fertilizer recommendation for an entire district or region.

Internal nutrient circulation: The approach comprises of various conventional practices like recycling of crop residues, either through direct application or as manure and cultivation of legumes often referred as integrated nutrient management in past. The practice of effective use of inorganic and organic sources of nutrients together in a proper proportion not only reduced the requirement of inorganic fertilizers, but also improved physical conditions of soil, enhances water retention capacity and its availability in the soil. Apart from this, the biological properties of soil and fertilizer use efficiency were also improved considerably.

Crop residues and manure: Incorporation of crop residues and natural vegetation in soil improved microbial activity during decomposition. Also adhesive action of decomposed products improved soil aggregation, hydraulic conductivity and moisture retention. Leaving the crop residues in soil generally showed a positive effect on grain yield. But, stover of pearl millet and sorghum which had low nutrient content were managed carefully, because they immobilized soil N at the peak requirement by crop which reduce its growth. In arid areas, cereal stover is often fed to livestock and manure is applied in field. This way of recycling the residues is more beneficial for crop than their direct application in field. Losses of N from such recycling systems are often high. First the cattle manure is aerobically decomposed and contain <1% N, and is applied in dry form and often showed a high sand content. Research showed that the most efficient use of manure is to combine it with some inorganic fertilizer. It provided readily available N, energy (carbon), and nutrients to the soil ecosystem, and improved soil structure, microbial activity besides reducing nutrient losses from leaching and denitrification. Soil microbes were valuable not only because they supply nutrients directly, but because they enhanced the synchrony of plant nutrient demand with soil supply by reducing large pools of free nutrients (and consequent nutriente losses from the system). Thus, microbes maintained a buffered, actively cycled nutrient supply. Substitution of 50% of fertilizer requirement by farmyard manure showed result in yield levels nearly similar to those obtained with complete fertilization. Simultaneous application of farmyard manure and inorganic fertilizers also showed a synergistic effect on crop yield.

Fig. 2. Intercropping of legumes in cereals improved soil fertility and water use efficiency

Cereal-legume crop rotation: Legume cereal rotations, intercropping of cereals and legumes are an important practice for restoring soil fertility on large land holdings (Fig.2). Cultivation of moong bean in rotation with pearl millet supplied with 20 kg N ha^{-1} gave similar yield as with application of 40 kg fertilizer N ha^{-1}. The amount of N returned from legume rotations depends on whether the legume is harvested for seed, used for forage, or incorporated as a green manure. Net N return to soil range from 23 to 110 kg ha^{-1} from pigeon pea, 23 to 50 kg ha^{-1} from dolichos beans, and 25 to 60 kg ha^{-1} from groundnut.

Pearl millet in rotation with cluster bean was reported to yield higher than its continuous cultivation. Pearl millet – cluster bean rotation also improved soil organic carbon by 12% and available soil P by 25%. Rotation of pearl millet with moong bean or cluster bean was better than its rotation with moth bean. The beneficial effect of legumes to pearl millet also depends on the number of seasons of their cultivation before growing pearl millet.

Mycorrhiza: It plays a very significant role in plant nutrition and stabilization in the rhizosphere of desert plants. Most species in families of Asteraceae, Fabaceae, Poaceae, Rosaceae and Solanaceae usually form endo-mycorrhizal associations in arid habitats. *Glomus deserticola* is indigenous to many desert soils. Most species of trees, *Opunitia* and *Euphorbia* showed > 50% infection by *Glomus* sp. and *Gigaspora* spp. In desert, incidence of arbuscular mycorrhiza infection varies with the availability of water and with composition of plant community. Vesicular Arbusidor Mycorrhiza (VAM) also helps in desert reclamation and soil stabilization. They link soil particles to each other and to the roots in part by producing glomalin, an important glue that holds aggregates together. Fungi provided VAM important pathway for improving the water-use efficiency of tree crops. It was documented that the inoculation of horticultural trees with *Glomus mosseae* enhanced their lateral root development, which in turn stimulated acquisition of water and nutrients.

Nitrogen-fixing trees: Leguminous trees can survive with arid soils' low levels of nitrogen (N) due to their nitrogen-fixing capacity. These trees can fix 43 to 581 kg N ha^{-1} year^{-1}, than 15 to 210 kg N ha^{-1} year^{-1} from grain legumes. Nitrogen-fixing trees such as *Acacia* sp. and *Prosopis* sp. are some of the best sources for N-enrichment in arid regions. Besides, most of these species are sources of highly nutritious fodder, fuel, food, charcoal, gums, fibre and timber. *Acacia* spp. are also well adapted to low rainfall and extreme temperatures due to their extremely deep root systems. They include about 1,250 species of deciduous or evergreen trees and shrubs widely distributed in the tropics and warmer temperate areas. These species are planted to provide windbreaks, afforest mining and salt-affected areas, stabilize sand dunes, and reduce erosion. Besides, nitrogen-fixing capacity, such species in agroforestry systems are beneficial for maintaining soil fertility due to their efficient nutrient cycling and uptake of nutrients from deep soil layers. Leaf pruning of these trees is an important component of sustainability in agroforestry and soil fertility due to addition of the biomass available from leaf fall. *Prosopis* spp. are deciduous, thorny shrubs or small trees native to tropical and sub-tropical regions of the western hemisphere, Africa, the Middle-East and India. Their deep rooting systems imparts them significant tolerance to water stress. This depth allows the roots to achieve good nodulation even under drought conditions, enabling them to survive and contribute to biomass maintenance in the soil. Nutrient levels (N,P, and K), moisture content, and organic carbon of soil are all higher under the canopy of *Prosopis cineraria* than open area. The beneficial effects of tree legumes can also be estimated indirectly through their effect on a neighbouring or following crop and is discussed under integrated farming systems. Leguminous trees, which were grown in hedgerows or intercropped with annual crops, improved soil water conditions as well as enhanced soil nitrogen (N) supplies. These trees obtain most of their water from deep soil layers whereas annual field crops take water from the upper layers. However, competition between leguminous trees and annual crops was reported from some dry areas of India which can be minimized by considering spacing related issues into management decisions.

Conservation agriculture: This aims to conserve and improve the natural resource base while using the resources available for agricultural production more efficiently. The conservation agriculture showed minimium soil tillage, maintains a permanent soil cover of crops and/ or residues, and utilized efficient crop rotations. This was least successful todate in the arid areas where production of organic matter is too low for permanent soil cover with crop residues because of water scarcity. But it was found that even small amounts of crop residues can reduce wind erosion considerably and increase soil water storage. Since significant quantities of soil and nutrients were lost by wind and water erosion under arid conditions where the soil remains bare for most part of the year, even small savings are worth pursuing. Interactions between soil nutrients and water are different under conservation tillage compared with conventional tillage systems. For example, nitrogen is more efficiently used under no-till than conventional tillage due to the higher soil moisture content conserved, especially with legume crops. This is mainly because no-till reduced water loss in dry years, due to the residue cover, and improved water infiltration during wet years. No dramatic increases in production and soil fertility was expected in arid areas in the short-term and farmers were unlikely to commit themselves to conservation agriculture without adequate incentives and policy support. Further, due to scarcity of crop residues the vacant space between rows can also be covered with plastic mulch which was a common practice in orchards (Fig. 3).

Fig. 3. Mulching and pressurized irrigation systems improved water use efficiency and productivity in horticultural crops

So long as food production remain a soil-based industry, there is no way that required yield increases of the major crops could be attained without ensuring that (*i*) plants have an adequate and balanced supply of nutrients, and (*ii*) the appropriate environment exist for nutrients to be available to a particular crop in the right form, in the correct absolute and relative amounts, and at the right time for high yields to be realized in the short-and long-term. This major functions of soil i.e. production of food and biomass is now under threat from the processes of production. Development of a soil policy is essential to provide food security and sustained economic growth of our country.

Optimal v/s resource availability based fertilization: Resource availability with farmers of arid zone is limited and extension agencies do not provide flexible fertilizer recommendation based on resource availability with farmers. This raised many questions like should the farmer optimally fertilize a part of the farm land with the available resource or should fertilize whole farm at sub-optimal level with the same quantity of resource. This was answered by a long-term experiment conducted at CAZRI for 21 years. Pearl millet was grown with two levels of manure (2.5 and 5 tonne ha^{-1}), two levels of urea (20 and 40 kg N ha^{-1}) and their combinations. Total grain production of pearl millet over 21 years was minimum in control and maximum (i.e. about 3-fold of the production in control) after application of 5 tonne manure +40 kg N ha^{-1} (Fig. 4). Total production in other treatments was in order of: 5.0 tonne manure +20 kg urea-N >2.5 tonne manure+20 kg urea-N >2.5 tonne manure+40 kg urea-N >5.0 tonne manure >2.5 tonne manure > 40 kg urea-N > 20 kg urea-N. These results suggested that when adequate resources were available, whole farm (say 2 ha) should be fertilized with 5 tonne manure +40 kg N ha^{-1} to achieve maximum production. But if only 5 tonne manure and 40 kg N is available, how should it be distributed in 2 ha land? Our results

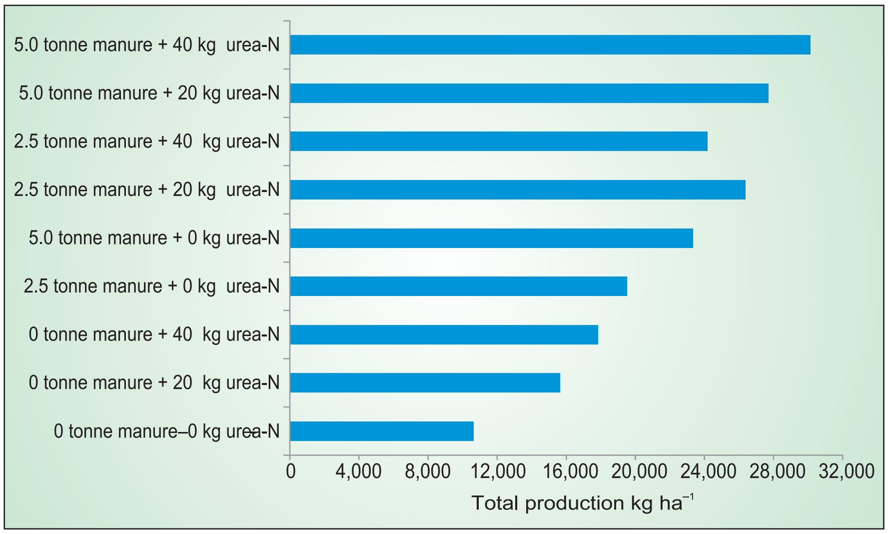

Fig. 4. Total grain production of pearl millet in 20 years (1996-2015) under different treatments

suggested that by application of 5 tonne manure + 40 kg N/ha in 1 ha land only and leaving other 1 ha unfertilized would give total production of 40,767.72 kg (10,638.70+30,129.02) from 2 ha land. On the other hand application of 2.5 tonne manure + 20 kg N in 2 ha would give a total production of 46,640.12 kg. Thus under limited resource availability, application of sub-optimal level on whole farm would give higher production over the years from the farm.

Some unusual aspects of nutrient cycles in arid land areas: Nutrient cycling in arid lands is affected by low and erratic rainfall, wide temperature extremes, sodicity and/or salinity, and occasionally by relatively high rates of dry deposition of nutrient-enriched soil particles from wind erosion. In extremely arid areas where vascular plants were few, nutrient cycling through microbial crusts predominated. Crust was generally composed of nitrogen-fixing cyanobacteria and micro-organisms which can survive long periods of desiccation with rapid responses to rehydration. These organisms conserve and cycle water as well as nutrients, increase water infiltration, slowdown evapo-transpiration, and reduce wind erosion. Some of the nitrogen (N) contributed by these organisms to the soil lost through denitrification from underlying anaerobic microsites, which consequently limits nitrogen build-up. Under certain conditions, nitrate accumulated in dry soils from repeated rainfall events followed by mineralization of litter and nitrification. This usually occured in the absence of vascular plants. ... of higher fertility occurred in the soil that could be exploited temporarily by fodder plants. In arid areas where plants grew, most of the nitrogen remains in the plants' biomass. Some potentially useful desert plants, such as *Atriplex* and *Artemisia* spp., inhibit nitrogen-fixing cyanobacteria and also conversion of nitrite to nitrate which had negative effects on the nitrogen-cycle. When these plants impede the oxidation of nitrite to nitrate, it leads to nitrite accumulation followed by denitrification, which resulted in gaseous nitrogen losses from the soil system. The possibilities for enhancing nitrogen (N) in arid land soils by use of legumes are also restricted by water availability as plants invest more energy in developing more extensive, deeper rooted systems to acquire water rather than in forming root nodules. This may be the reason that there are only a few evidences to showed high soil N in spite of dominant presence of native legumes. Certain legume phreatophytes, such as *Prosopis* spp., that had very deep roots to exploit deep water sources in dry areas. Often had nitrogen-fixing activity even when the upper soil layers contain high levels of soil nitrate that would normally inhibit plants' nitrogen-fixation. These examples suggested that one needs to assess nutrient cycling under arid conditions carefully.

Shrubs as islands of fertility and biodiversity: In arid ecosystems where plants are sparse, a shrub is often a conspicuous component of the ecosystem. As wind moves across the landscape the canopy of the shrub disrupt the currents and in process the fine dust, often rich in nutrients gets accumulated on leaves which later move through the canopy to the under canopy soils along with precipitation. Thus rainfall below the canopy showed to contain up to 10-fold more nutrients than bulk precipitation occurring outside the shrub canopy. Thus, intercepted dust fertilize the under canopy soils. Besides, shrubs become nest sites for birds and provide shade, and food resources for animal populations, which could enrich the local soils through faeces, discarded carcasses, and nest materials. Shrubs are also important for the interception, infiltration, and storage of water, thereby increasing soil moisture. Finally, the shrub itself contributed to the enrichment of soil nutrients. Besides, litter production, root exudates and deadfall all contribute to enriching the soils in the vicinity of the shrub. Thus shrubs in arid lands are often referred to as 'islands of fertility'. They also acted as a cradle for biological diversity. Shrub zone soils tended to support a higher abundance of macro-invertebrates, microflora and nematodes. Some recent studies showed that the differences between the shrub associated communities and interspaces were primarily due to a difference in the abundance of the species rather than the member of the communities. The shrub canopy soils harbour roughly the same bacteria and fungi as interspace soils, but the structure of the community differs.

Thus, appropriate moisture conservation interventions coupled with adoption of practices for internal nutrient circulation in arid zone shall compensate for most of the burden of external nutrient inputs so as to achieve sustainable crop productivity.

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