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Role of Soil Moisture in Fertilizer Use Efficiency for Rainfed Areas-A Review

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Abstract:
The balanced dose of fertilizer used for any crop to get the desirable yield is very much important in crop production and is dependent upon different factors like soil type, soil texture, soil structure, organic matter and especially soil moisture availability is the main and crucial factor in predicting optimum use of fertilizers. The areas where proper irrigation practices are available and the moisture level differences are minimum, there the prediction of fertilizer is simple and depends upon soil type, availability of different nutrients and organic matter in the soil which helps to estimate nutrient deficiencies to be supplemented by different fertilizers with optimum dose. Commendable job has been done by scientists of University of Agriculture, Faisalabad to design a model to predict fertilizer doses for all districts of Punjab for different cropping pattern with the help of some basic soil fertility status (organic matter, available phosphorus) assuming no water shortage during crop growth period. Rainfed/barani tract comprises 3.10 million hectare (mha) out of total 11.83 mha under cultivation in Punjab. Therefore, the areas where irrigation practices are not present and the crop production is entirely dependent upon uncertain and uneven distribution of rainfall which makes the agriculture risky and the farmers are reluctant to incur expenditure on expensive inputs especially fertilizers, so one cannot rely only on basic soil fertility status. The fertilizer doses vary according to moisture available at the specific site besides other factors and one cannot use only soil type and nutrient levels for fertilizer dose prediction to get maximum and desired yields. In order to address this issue work done by different scientists is reviewed to establish the relationship or role of soil water contents in fertilizer use efficiency in rainfed areas to design a future study to predict different fertilizer doses under different prevailing soil water contents to achieve desired yield targets.

Key Words: Fertilizer use efficiency, rainfed, moisture, model

1. Introduction:

The fertilizer use efficiency in Pakistan is quite low and highly variable under different soil and climatic conditions. Fertilizers have been mostly subject of irrigated agriculture. In rainfed conditions it is common notion among farming community that fertilizer application is of little value and fertilizer use efficiency has not been investigated under such environments. A nutrient is available, only when it is soluble in water. In the regions of adequate rainfall/irrigation, main thrust is to make the nutrients more and more soluble in the water, so that the plant roots may absorb them. But in dryland areas problem is just contrast. These soils do not have enough moisture to dissolve plant nutrient, even if the nutrient is present in the soil in water soluble form. Therefore, nutrients in the soil do not find their way into the plant roots. Application of fertilizers is, therefore, highly restricted in dry land areas. The scarcity of water in these areas greatly inhibits adoption of modern package of practices in farming including the use of high yielding varieties, pesticides and fertilizers. Consumption of fertilizers per hectare in dryland regions is nearly 3 to 4 times lesser than that in irrigated areas. Researches have, however, proved that the productivity of drylands can be improved significantly by adopting appropriate method of fertilizer application. Farmers in dryland areas are very receptive to fertilizers. Yet, a large number of them stay away from fertilizers as the use of fertilizers involves a risk because of uncertainty of rainfall and moisture availability. Drylands have not only a thirst for water but also a hunger for nutrients. Nitrogen deficiency is a widespread problem of dryland areas. Low amount of moisture in the soil and relatively higher temperature encourage the loss of nitrogen from the soil. Soil nitrogen is lost to the atmosphere in gaseous form. Efficiency of urea and solutions appeared to be increased by rain immediately after application (Volk, 1966).

The economic approach to decide about the most desirable prediction of fertilizer dose to enhance crop productivity is to use principles of economic efficiency to ensure that fertilizer is supplied to its most valuable doses. It is, therefore, necessary to have theoretically sound estimates of the exact amount of fertilizer in its different doses. Nutrient efficiency is widely being used as a measure of the ability of a plant to obtain and utilize nutrient for biological and grain yield. It is generally assumed that higher phosphorus supply is a requirement for the prediction of high yield potential of different crop cultivars (Clark, 1990), because it plays a critical role in energy saving and transfer through and among the cells, enhances root development, facilitate greater nitrogen uptake which resulted in higher grain protein. Phosphoric fertilizer at the time of application to soil, after mixing with moist and properly decomposed farm yard manure (FYM) in the ratio of 1:2, resulted in 30% higher phosphorus use efficiency (Anonymous, 2003). Post sowing phosphorus application in 5% or diluted form solution along with irrigation water is even better for phosphorus use efficiency (Zafar *et al*., 2003). The fertilizer efficiency improved significantly, when integrated (organic and inorganic) source of phosphorus was used (Yamoah *et al*., 2002). The use of farm yard manure (FYM) improved soil organic matter and the chemical, physical and microbial properties of soil, ultimately affecting the phosphorus uptake of plants (Belay *et al*., 2001). Among other practices that effect efficiency of fertilizer, its time and method of application are also critically important. Previous studies have been demonstrated that soil moisture data when combined with vegetative crop characteristics may be used for estimation of crop yield potential, which resulted in more accurate fertilizer recommendations. Accurate mid-season soil moisture data combined with Normalized Differences Vegetative Index (NDVI) data improved the prediction of final grain yield (Karaman *et al*., 2001).

Mostly it is considered that soil nutrition can be a constraint under moisture stress. Negative interaction between phosphorus and water shows that increasing phosphorus could enhance drought resistance in crops under water stress conditions (Du *et al*., 2003). Low soil moisture affects practically every aspect of plant growth, modifying their anatomy, morphology, physiology and biochemistry according to the nature of plant. Soil moisture not only affects the physio-chemical activities of plant but also regulates the availability and translocation of nutrients to various organs of the plant and thus alters plant growth. Hence, adequate and timely irrigation is one of the most important cultural practices that should be considered necessary for successful crop husbandry. Crop water requirements and its responses to irrigation vary with the nature of soil, crop variety, growth stage, climatic conditions and management practices.

Crop production in water stressed conditions depends on rainfall (Farahani, 1998 and Sandhu *et al*., 1992). Thus enhancing soil water storage ability and water conservation in such regions may be one of the most crucial agricultural management practices (Mosavi *et al*., 2009). For this, it is necessary to improve soil structure and facilitate water infiltration into the soil for increase water use (Martens & Franken, 1992). It was reported that organic matter has a prominent role in aggregate formation and soil structure stability (Pikul *et al*., 2005; Annabi *et al*., 2007). Gravity controls the movement of water into the soil, along with capillary action, and soil porosity. Soil porosity is regulated by its texture, structure and organic content (Martens & Franken, 1992). Total amount of decayed organic matter found at the soil surface can also be resulted in enhancement of infiltration. Generally organic matter is more porous than mineral soil particles and it can hold much greater quantities of water (Martius, 2001).

The reliability of any nitrogenous fertilizer recommendation depends upon the amount of water supplied to the soil. For irrigated crops, nitrogen recommendations are based on the assumption that the water is distributed equally throughout the field and proper irrigation scheduling is practiced which supplies sufficient water to satisfy evapo-transpiration requirements without excessive leaching. Excessive irrigation will cause NO3-N to leach out of the root zone resulting in decreased nitrogen availability for crop use. Higher or supplemental rates of nitrogen fertilizer may be applied to compensate for leaching losses (James & Topper, 2010).

When plant growth is limited by unavailability of irrigation water then the nitrogen requirements are lower. Nitrogen requirements for dryland crops depend on the conserved soil water content at the beginning of the season along with any rainfall that occurs during the growing season. The heavy precipitation period may result in significant yield increase in dry-land grain production with concomitant increases in optimum nitrogen fertilizer rates, up to 70 lbs N/acre on spring wheat, for example. However, when it is dry, the amount of nitrogen recommended may be 25-50 lbs acre1. Soil moisture availability must be considered in determining the appropriate N recommendations for every crop and field situations (James & Topper, 2010).

Due to the interactions between soil water and nitrogen, it is impossible to specify the best level of nitrogen fertilization until soil moisture management practices (irrigation practices, irrigation rate and frequency of irrigation and/or the climatic regime) are well defined. Excess irrigation water results in loss of some soil nitrogen so fertilizer rates must be increased to compensate for the lowered fertilizer efficiency. When too little water is available (drought conditions), plant demand for nitrogen will be decreased (Doorenbos & Kassam, 1979).

The fertilizer requirement of plants varies depending upon the rainfall received during crop season (sowing to harvest), runoff and soil moisture stress parameters. An optimal dose based on a suitable soil water balance model would be more efficient compared to a general fertilizer dose. Therefore, it is required to derive crop season moisture stress index based on daily rainfall and runoff and then calibrate optimal fertilizer requirement for different plants (Victor *et al*., 2003). Multiple regression models of seed yield through rainfall, runoff and soil moisture stress index together with fertilizer variables could be calibrated for both prediction of seed yield and optimization of fertilizer at varying moisture stress levels (Draper & Smith, 1973; MaruthiSankar, 1986; Hanumantha Rao *et al*., 1993).

2. Fertilizer use under dryland conditions:

The total cropped area of Pakistan is 22 mha, out of which 4.22 mha is rainfed. Substantial improvement in crop yields is possible in rainfed areas receiving about 250mm rainfall and above if proper management techniques are adopted. The cropping pattern in rainfed areas is primarily determined by rainfall distribution. About 70 percent of the total rainfall receives in summer months/Mon soon and the rest in winter. The fertilizer efficiency in rainfed agriculture is comparatively lower than irrigated agriculture because of uncertainty of moisture at critical growth stages and poor management (Nisar & Rashid, 2003).

Like irrigated areas, almost all the soils of rainfed tract are deficient in nitrogen. Likewise more than 80 percent soils contain less than 5 mg kg-1 of available P indicating acute deficiency of this nutrient. Potash status was considered as satisfactory but deficiencies are reported recently. The use of fertilizers in rainfed areas is 3 to 4 times low compared with irrigated regions, further the use of phosphate is very low (Table 1). These data clearly show that most of the farmers in rainfed area are not using fertilizer at all (Nisar & Rashid, 2003). (Table 1)

There is a general perception that fertilizer pays less in rainfed tract because of uncertainty in the availability of moisture. It could be true to some extent if moisture is not properly managed. The efficiency of fertilizer is very much dependent on the skill to conserve moisture as well as improved cultivation methods and management practices (Nisar & Rashid, 2003).

Water contents of soil affect the availability of all nutrients. In dry soil condition, biological activity is slowed down, which affects the release of nutrients by decomposition of organic matter. The cations are more tightly bound to soil colloids and therefore less available to plants. In water logged soils, the concentration of ammonium ions, iron, phosphorous and manganese increase but nitrate contents fall because of denitrification (Nisar & Rashid, 2003).

3. Soil water and nutrient absorption/uptake

Water is a key factor in all the three mechanism of nutrient uptake i.e. mass flow, root interception and diffusion. Mass flow of soil water transports most of the nitrate, sulphate, calcium and magnesium to roots. Root also intercepts nutrients in moist soils. However, phosphorous, potassium and most of the micronutrients are not adequately absorbed by these two methods. A third method, diffusion, is important. The plant absorbs nutrients close to the roots and a concentration gradient is established. Thus nutrients diffuse slowly from areas of higher concentration to area of lower concentration. This occur through water films, hence rate of diffusion depends partly on the water contents of soil. With thicker water films in the soil, nutrients can diffuse more readily (Nisar & Rashid, 2003). Efficient use of nutrients after uptake depends on continuous supply of moisture, otherwise transport of nutrients within the plants can be restricted and their use for metabolic activities and plant biomass production will also be limited.

4. Soil water contents and Fertilizer use efficiency

The response of crops to fertilizer is higher where supply of irrigation water is ensured than in rainfed conditions (Nisar & Rashid, 2003). Figure 1 shows that response of wheat to fertilizer is high in irrigated areas than in rainfed areas. (Figure 1)

5. Soil and Environmental Conditions Affecting Fertilizer Use Efficiency

Nitrogen is subjected to a range of factors which decreases its uptake by plants including immobilization, denitrification, leaching, volatilization and runoff. Phosphorous uptake by plants is primarily influenced by fixation and to a lesser extent runoff and leaching. In general, enhanced efficiency fertilizer have feature which reduce the susceptibility of the fertilizer to one or more of these loss pathways. Nitrogen is taken by plants in either nitrate (NO3-) or ammonium (NH4+) forms (and potentially limited foliar uptake through stomata of urea (CO (NH2)2). Phosphorous is taken up as orthophosphate anions (H3PO4- and HPO42-).These forms can be highly reactive in soil and quiet susceptible to loss, fixation or immobilization. Therefore, enhanced efficiency formulation will gradually release these ions from fertilizer, hopefully timed to match crop demand, or will protect these forms of nutrients from reacting in soil to reduce their availability to plants. These reactions are influenced by soil temperature and moisture, so there is less reaction occurring with dry, cold soil conditions than with warm, moist conditions (James & Topper, 2010).

6. Water-fertilizer interactions

The influence of water on plant growth and nutrient use is complex, and to a large extent the processes are interdependent. An extreme deficiency of soil water could cause wilting and ultimate death of the plant. But, before such obvious effects set in, the status of nutrients in the soil and the soil's ability to get them may be impaired (Viets, 1974).In the arid and semi-arid areas of the world, more fertilizer is used where facilities for supplemental irrigations exist. For example, Tandon (1981) showed that irrigated areas form the major loci of fertilizer use.

Significant interactions between moisture and nutrients have been recorded with various crops (Singh and Prihar, 1978; Meelu *et al*. 1976). Depending on the available soil moisture, its management, and fertilizer application rates, crop yields comparable with irrigated agriculture have also been demonstrated. Meelu *et al*. (1976) showed that, for rainfed wheat in Punjab, higher doses of N could be profitably used in medium-textured soils with good moisture storage (Figure 2). In investigations on the effect of nitrogen and irrigation for summer sorghum, Venkatachari *et al*. (1976) showed that the increase in yield was 1100 kg ha^{-1} from irrigation alone, 2300 kg ha^{-1} from 80 kg N at the lower levels of seven irrigations, and 4900 kg ha^{-1} when 80 kg N and 16 irrigations were given.

Jha & Sarin (1981) found, in an all-India analysis, that farmers favored fertilizer use on heavier soils which retain more water than lighter soils, and that the percentage area fertilized correlated with rainfall. They also found, in a study of selected villages, that irrigation and rainfall during the growing season were the primary determinants for fertilizer use in Sholapur (in an area of in dependable rainfall) but not in Akola (in an area of dependable rainfall), where in none of their equations rainfall appeared as a significant variable. (Figure 2)

Under Mediterranean conditions, fertilizer recommendations are tuned to the average rainfall incidence. For example, for rainfed wheat in Turkey in the lower rainfall areas the fertilizer application is restricted to 40 kg P2O5 ha^{-1}; under good rainfall conditions it is 60 kg N + 40 kg P2O5 ha^{-1}. For high yielding varieties under irrigated conditions the recommendation is 80-100 kg N + 60 kg P2O5 ha^{-1} (De Geus, 1973). In Jordan fertilizers are mainly used for irrigated wheat in the Jordan valley, but small amounts are used in the dry regions with over 450 mm /year of rainfall. In the fertilizer demonstration trials in Morocco for dryland barley in the southern and northern regions, the N P K treatment of 20 - 60 - 0 was found to be best, while for irrigated barley the treatment 20-40-40 was the best (De Geus, 1973).The interaction between water and nitrogen was described by Van Keulen (1981) as follows: ‘Growth under nitrogen deficient conditions implies a slower rate of accumulation of dry matter, which, combined with a different distribution of the material, leads to a prolonged period in which vegetation does not cover the soil completely. Under such conditions, direct soil evaporation is longer than under non deficient conditions where a closed canopy is reached earlier. The amount of moisture available for transpiration is thus smaller under nitrogen deficient conditions. Rehatta *et al*. (1979) showed that moisture shortage with equal availability of nitrogen led to reduced uptake of the element showing, thereby, that uptake must be governed by the reduced rate of dry matter production. Hence moisture shortage to plants was assumed to have both a direct as well as an indirect effect on nitrogen uptake: in one case governed by the physical transport processes in the soil, and in the other by the metabolic processes in the plant Van Keulen (1981).

7. Crop growth response to moisture stress in relation to water use efficiency and fertilizer use efficiency:

Khondaker *et al*. (1983) imposed moisture stress ranging from field capacity to wilting co-efficient at different growth stages to study its effect on the availability and uptake of N, P and K by wheat plants, growth, yield and quality of wheat under fertilized and unfertilized conditions. Stress imposed beyond field capacity to 1/2 field capacity decreased N and P availability and their uptake. However, K availability and uptake was little affected by moisture stress. Wheat plant grew well and produced better yield at moisture levels of field capacity and field capacity to half field capacity as compared to other moisture stress treatments. Moisture stress of half field capacity to wilting co-efficient and 1/3 field capacity to wilting coefficient resulted in harmful effect on crop growth and yield. Moisture stress conditions imposed at tillering, flowering and harvesting stages were responsible for moderate adverse effects on the crops.

Sharma (1985) observed that average grain yield of wheat increased from 1600 kg ha^{-1} to maximum of 1700 kg ha^{-1} as soil moisture tension (SMT) decreased from 4.0 to 1.5 bars. With the application of N @ 40 and 80 kg ha^{-1}, grain yield of 1400 and 2000 kg ha^{-1}, respectively was recorded by decreasing SMT, the yield increased in the range of 1900-2400 and 2000-3000 kg ha^{-1} with 40 and 80 kg N ha^{-1}, respectively. Ahmad *et al*. (1985) conducted field experiment in wheat by subjecting the soil to three moisture levels i.e. 1, 4 and 7 bar tension and four fertilizer levels of 67-34-34, 67-67-34, 134-34-34 and 134-67-34 kg NPK ha^{-1}. The maximum grain yield of 5710 kg ha^{-1} was achieved when the crop was irrigated at one bar tension and 134-67-34 kg NPK ha^{-1} was applied. It was also observed that with the increase in moisture tension, the yield decreased at each fertilizer level. Maruthi Sankar *et al*. (2008) on the bases of six field experiments conducted on sunflower with treatments combinations of 4 dates of sowing (DOS), 3 moisture conservation methods (MC) and 3 levels of fertilizer NP indicated a positive correlation of seed yield with rainfall in all 4 DOS. Negative relation of moisture stress index (MSI) was found with yield under all the 12 combinations of DOS and MC methods. The relation between rainfall (RF) and runoff (RO) was positive, while MSI had negative relation with both RF and RO. Subhani *et al*. (2012) conducted experiments under rainfed conditions for consecutively five years with different cropping patterns and agronomic practices to find a feasible cropping pattern that could enhance profitable crop intensity and fertilizer use efficiency in these areas and confirmed a positive and significant relationship between soil water content over summer and the yields of wheat and chickpea crops in winter with enhanced nutrient uptake. While eliminating summer fallow adversely affected soil water content, wheat yield and economic return.

8. Water use efficiency and fertilizer use efficiency under different fertilizer and moisture levels

Laghari *et al*. (1979) conducted two field experiments during 1975-77. The soil was subjected to three levels of moisture depletion i.e. 50, 70 and 75 percent, respectively with four fertilizer levels of 0-0-30, 50-25-30, 100-50-30 and 100-75-30 kg NPK ha^{-1} in 1975-76 and three moisture depletion level 70, 80 and 90 percent, respectively with four fertilizer level 120-0-30, 120-60-30, 60-0-30 and 60-60-30 kg NPK ha^{-1} in 1976-77. They observed that maximum grain yield of 3250 kg ha^{-1} was obtained when crop was irrigated at 50% moisture depletion and 100-50-30 kg NPK ha^{-1} was applied in 1975-76, while a maximum yield of 3480 kg ha^{-1} was obtained when wheat crop was irrigated at 70% moisture depletion with 120-60-30 kg ha^{-1} fertilizer levels in the next year.

Ahmad *et al.* (1989) studied the effect of water and fertilizer on wheat crop. In a field experiment they applied fertilizer @ 67-34-34, 67-67-34,134-34-34 and 134-67-34 kg NPK ha^{-1}, respectively at three different moisture depletion i.e. 40, 60, and 75 percent. Highest grain yield was obtained with a treatment combination of lowest moisture depletion (40%) and highest fertilizer dose of 134-67-34 kg NPK ha^{-1}. They also observed that in spite of reduction in yield at higher depletion, fertilizer response was positive.

9. Conclusions

The fertilizer efficiency in rainfed area is comparatively lower than irrigated agriculture because of uncertainty about moisture at critical growth stages and poor management. There is a general perception that fertilizer pays less in rainfed tract because of uncertainty in the availability of moisture. It could be true to some extent if moisture is not properly managed. Water contents of soil affect the availability of all nutrients. In dry soil condition, biological activity is slowed down, which affects the release of nutrients by decomposition of organic matter. The cations are more tightly bound to soil colloids and therefore less available to plants. Water is a key factor in all the three mechanism of nutrient uptake i.e. mass flow, root interception and diffusion. Efficient use of nutrients after uptake depends on continuous supply of moisture, otherwise transport of nutrients within the plants can be restricted and their use for metabolic activities and plant biomass production will also be limited. The response of crops to fertilizer is higher where supply of irrigation water is ensured than in rainfed conditions. Crop water requirements and crop responses to irrigation vary with the nature of soil, crop variety, stage of growth, climatic conditions and management of crop.

A model to predict optimum fertilizer doses for Punjab districts was recently developed by the scientists of University of Agriculture, Faisalabad with the help of some basic soil fertility statistics assuming no water shortage during crop growth period. Here, an important factor i.e., soil moisture content was overlooked, so the areas where crop production is completely rely upon rainfall and the farmers do not spend much on fertilizers, cannot use this model. The fertilizer efficiency is directly correlated with soil moisture availability at its application or during the growth period at the specific site besides other factors and one cannot use only soil type and nutrient levels for fertilizer dose prediction to get maximum and desired yields. To overcome this problem, a new fertilizer prediction model is needed to be developed for rainfed areas based on soil moisture content of that specific area besides other factors like soil type, soil fertility status and previous crop etc. to achieve desired yield target.

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Table 1: Use of NPK (kg ha^{-1}) in different areas of Punjab and NWFP during 2000-01 (Nisar & Rashid, 2003)

Region	N	P_2O_5	K_2O
PUNJAB (IRRIGATED)			
Cotton-Wheat (region)	116	24	1
Mixed crops (region)	99	20	2
Rainfed-Punjab			
Pulses-wheat (region)	31	7	-
Maize-wheat (region)	19	4	-
NWFP (IRRIGATED)			
Mixed crops (region)	123	27	0.5
Rainfed-NWFP			
Pulses-wheat (region)	19	4	-

Figure 1: Fertilizer response of irrigated and rainfed wheat in Pakistan (Nisar & Rashid, 2003)

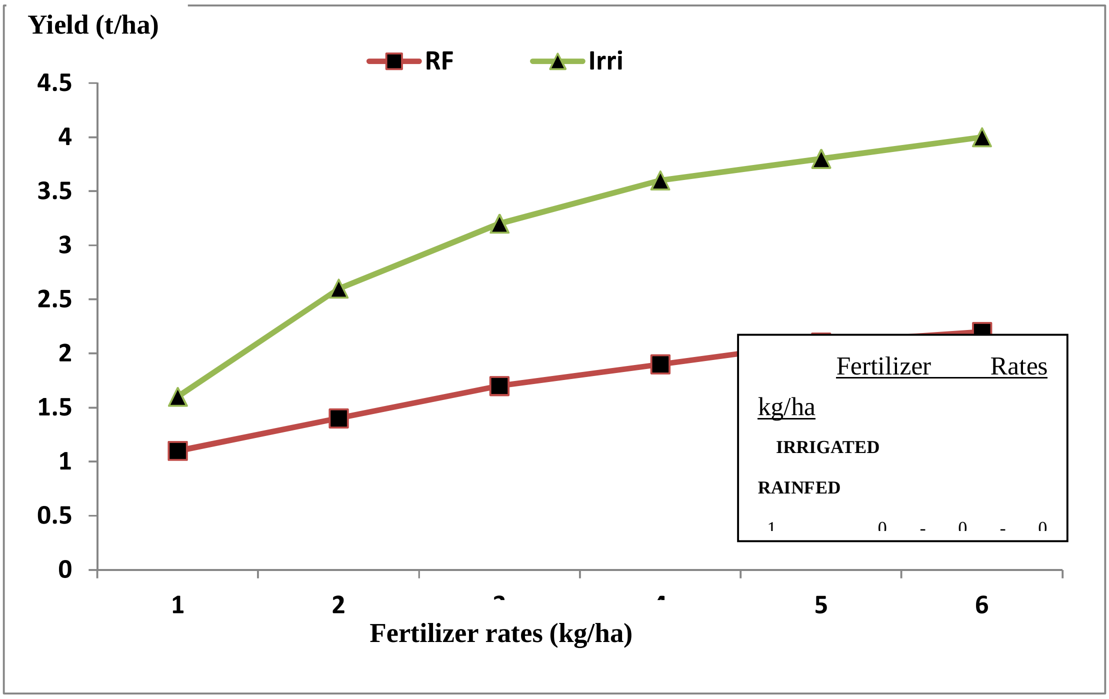

Fig. 2: Response of rainfed wheat to nitrogen on soils having different stored moisture (M1, M2, M3) (From Meelu *et al.*, 1976)