STATUS AND AVAILABILITY OF SULPHUR IN THE MAJOR PADDY SOILS OF KERALA AND THE RESPONSE OF RICE TO SULPHATIC FERTILIZERS

By

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THESIS

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DECLARATION

I hereby declare that this thesis entitled **"Status and availability of sulphur in the major paddy soils of Kerala and the response of rice to sulphatic fertilizers"** is a bonafide record of research work done by me during the course of research and that the thesis has not previously formed the basis for the award to me of any degree, diploma, associateship, fellowship or any other similar title of any other University or Society.

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Certified that this thesis entitled "**Status and availability of sulphur in the major paddy soils of Kerala and the response of rice to sulphatic fertilizers**" is a record of research work done independently by **Sri.N.Purushothaman Nair**, under my guidance and supervision and that it has not previously formed the basis for the award of any degree, fellowship or associateship to him.

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(N. PURUSHOTHAMAN NAIR)

Dedicated to

fond memories of my mother

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Introduction

1. INTRODUCTION

Sulphur is an essential plant nutrient gaining international importance. During past two decades interest in sulphur as a plant nutrient increased dramatically with more frequent occurrence of sulphur deficiencies. Increased use of high analysis fertilizers containing little or no sulphur, multiple cropping and high yielding varieties which remove greater amount of sulphur from the soil, use of crop residues for feed and fuel, declining reserves of soil sulphur and decreased use of sulphur containing pesticides have contributed to this growing need for application of sulphur as a nutrient, which hitherto was not a concern in fertilization.

A complete assessment of sulphur nutrition involves, soil, plant and animal phases and the inter-relation of all the three, since it is a constituent of plant proteins so valuable in animal nutrition. Sulphur is a component of amino acids - methionine, cystine and cysteine; growth regulators, thiamine and biotin; and glutathione, which is important in oxidation reduction reactions.

Under the changing scenario from sufficiency to deficiency it is essential to quantify the magnitude and extent of sulphur deficiencies; further more, sulphur containing fertilizers should be evaluated to determine the more suitable source both agronomically and economically under different growing conditions (Morris, 1988).

Tandon (1991) summarised results of soil analysis in Kerala and reported that sulphur deficient soils were found in all the districts in Kerala which ranged from 20 per cent in Thiruvananthapuram to 55 per cent in Palakkad.

Studies conducted in Agricultural Research Station, Mannuthy revealed that rice crop responded to sulphatic fertilizers. However detailed studies were suggested to confirm this finding by selecting sulphur deficient soil for field experimentation (George, 1989).

Rice is the major food crop of Kerala in area wise and is cultivated in 6.6 lakh hectares. The major rice growing soils in Kerala are grouped as alluvial (Entisols) and brown hydromorphic or low land laterite (Inceptisols) soils (Anon, 1978 and Anon, 1984) and the bulk of the area falls in the districts of Palakkad, Thrissur, Ernakulam and Alappuzha.

No systematic work on the status of sulphur and its availability to rice in the alluvial and brown hydromorphic paddy soils of Kerala has been reported so far.

It is in this circumstances, a holistic study on sulphur nutrition of rice in Kerala by series of investigations were taken up with the following objectives:

i) to assess the sulphur status of major paddy soils of Kerala (alluvial and brown hydromorphic),

ii) to determine the critical level of sulphur in these two types of soils,

iii) to identify a suitable soil test procedure for sulphur estimation in these two type of soils,

iv) to study the response of rice to different sources and levels of two popular sulphatic fertilizers viz., ammonium sulphate and ammonium phosphate sulphate and

v) to assess the sulphur use efficiency of rice.

Review of Literature

2. REVIEW OF LITERATURE

Sulphur requirement of rice is comparatively less studied as rice was being nourished with sulphur indirectly through sulphur containing N, P and K fertilizers and the crop's need of sulphur was comparatively low. In this chapter an attempt is made to review briefly the available literature on sulphur status of soils, methods of estimation of available sulphur in soils, sulphur response and use efficiency studies, mostly confining to rice.

2.1 Sulphur status of soils

It is estimated that earth's crust contains 0.06 per cent sulphur and its distribution in soils vary from zero to over 500 ppm (Starkey, 1950). Many agricultural soils of humid regions have shown to contain little inorganic sulphate in the surface horizons. But in drier areas calcium sulphate can accumulate in the profile (Freny *et al.*, 1962). The total sulphur content of surface soils of India can vary from 19 ppm to 3836 ppm (Tandon, 1987).

Major portion of total soil sulphur is in organic form which must undergo mineralization before becoming available to plants (Blair *et al.*, 1978).

On studying the different forms of sulphur in the Malaprabha command area of Karnataka, Balanagoudar and Sathyanarayana (1990) observed that 51 per cent of soil fell under low category when 10 ppm SO_4-S was considered as critical limit.

In general, sulphur status of the soil is determined by estimation of available SO_4-sulphur, total sulphur, adsorbed sulphur and organic sulphur. For this the SO_4-S fraction is determined by extraction with 0.15 per cent $CaCl_2$. The adsorbed sulphate is estimated from the difference between phosphate extractable sulphur and calcium chloride extractable sulphur. The organic sulphur is the difference between total sulphur and phosphate extracted sulphur (Misra *et al.*, 1990, Arivazhagan *et al.*, 1991 and Balasubramanian *et al.*, 1991).

2.1.1 Available sulphur

Most of the sulphur in soils is in the organic form but neither total sulphur nor organic sulphur has proved to be a satisfactory index of soil S availability to growing plants (Williams and Steinbergs, 1964). Methods to measure the "available S" by extraction with different extractants have been used successfully by many workers to assess the sulphur deficiency of soils (Westermann, 1974).

Studies on soil sulphate as an index of sulphur availability, suggested that a prediction based on a 'critical' level of 6.0 kg $CaCl_2$ extractable sulphate sulphur ha^{-1} in a 0-15 cm soil depth was accurate for approximately 80 per cent soils (Walker and Doornenbal, 1972).

Effect of intensive cropping and fertilizer use on the crop removal and availability of sulphur was studied for seven years at IARI from 1971 to 1978. It was observed that there was a marked depletion by 54.8 to 67.1 per cent in available S in soil in all the treatments except the one where sulphur was being supplied every year (Rao and Ghosh, 1981).

Available sulphur status decreased from 20 to 9.5 ppm when S free NPK fertilizers were used for 13 years where as it increased to 30.8 and 39.5 ppm respectively when NPK fertilizers containing 45 and 67.5 kg sulphur were applied per hectare per season (Sahoo and Panda, 1987). Similar findings have been reported by Helkiah *et al.* (1987).

Studies on the available sulphur status of different agroclimatic zones of Himachal Pradesh showed that highest average amount of sulphate sulphur (17 ppm) was present in subhumid tropical zone followed by (13.3 ppm) wet temperate zone and lowest (11.7 ppm) in humid tropical zone (Sharma *et al.*, 1988). It was observed that soluble SO_4-S formed a small fraction of total sulphur (i.e. 1.25%) (Singh *et al.*, 1993).

2.1.1.1 Availability of sulphur under flooded condition

Rice plants grown in the flooded soil had a lower S content than those grown on the same soil without flooding. That was because the plant could use only the SO_4^{-2} ions as its source of sulphur and in flooding SO_4^{-2} are reduced in the anaerobic condition (Nearpass and Clark, 1960).

Under flooded conditions due to limitations of oxygen the sulphide concentration increases to a high amount and combines with iron in soil to form iron sulphide and this is retained in the soil which results in less evoluation of H_2S gas (Sachdev and Chhabra, 1974).

Submergence generally decreases sulphur availability. Under low Eh conditions sulphate can be reduced to sulphides which in turn can be tied up as insoluble iron or manganese compounds (Feng and Ye, 1981).

While discussing the kinetics of water soluble SO_4, Ponnamperuma (1981) explained that acid soils showed first an appreciable increase of water soluble sulphate followed by slow decline to a final concentration of 1 ppm, 16 weeks after flooding.

Sulphur removal through leaching is suspected to be an important route of sulphur exit in coarse textured soils under high rainfall and or flood irrigation (Tandon, 1986).

Status of different forms and deficiency of sulphur in different types of soils of eastern U.P. showed that fifty seven per cent soil samples were low in plant available sulphur and only 0.52 per cent samples have shown high amount of available sulphur status (Tiwari and Pandey, 1990).

Marked variation on the available sulphur status during the crop season has been reported by researchers. The highest availability in soil was at maximum tillering stage of rice, which was gradually decreased with the advance of crop growth (Clarson and Ramaswamy, 1992).

2.1.2 Total sulphur

Total sulphur content of soils is an indication of sulphur supplying capacity of soil. However, total sulphur content has shown little promise as an index of available sulphur (Freney *et al.*, 1962). So, several workers have attempted to measure a labile fraction of organic sulphur.

Studies on the sulphur status of 13 rice soils from different Model Agronomic Experimental Centres indicated that the total sulphur ranged between

112.5 to 275 ppm. It was further noticed that, there was significant correlation between total sulphur and uptake of sulphur by no sulphur plants [control] (Venkateswarlu and Subbiah, 1969).

A study on the status and distribution of sulphur in soils of Rajasthan by Rahul and Paliwal (1978) showed that the total sulphur in the profiles ranged from 100 to 3250 ppm. The extraction of sulphur with different extractants revealed that the maximum sulphur extracted was only 2.7 per cent of the total. Thus 97 per cent of the total S remained unextracted or in unavailable form. It was also noticed that on individual soil group basis, the S supplying power was quite wide, varying from 0.64 per cent in medium black to 8.77 per cent in desert soil.

In orchard soils of Uttar Pradesh the total sulphur content ranged from 97.5 and 187.5 ppm, where as the concentration of sulphate sulphur was 16 to 32.5 ppm (Singh and Sharma, 1983).

The total S content of Kuttanad rice soils of Kerala (which is 1 metre below MSL) varied between 600 and 9900 ppm with a mean value of 2324.1 ppm (Mathew, 1989).

Studies on the different forms of sulphur in the entisols and vertisols of Gujarat showed that the total sulphur content ranged between 25.7 and 925 ppm (Misra *et al.*, 1990).

In Himachal Pradesh studies on the 10 representative groups of soils showed that the total sulphur and SO_4-S ranged between 160.6 to 325 ppm and 5.5 to 21.2 ppm respectively (Tripathi and Singh, 1992).

The sulphur status of rice growing soils of Kanpur, Aligarh and Mathura districts showed that the S content ranged between 104 and 179 ppm in samples collected from the depth up to 25 cm. The same were between 110 to 170 ppm in the soil samples collected in the depth between 25 cm and 50 cm (Hariram *et al.*, 1993).

The sulphur status of 120 soil samples collected from 20 locations in North Kashmir indicated that the total sulphur contents of soils were in the range of 139 to 226 ppm with an average of 183 ppm (Kher and Singh, 1993).

An investigation to quantify the forms of sulphur in the uplands, mid lands and low lands of Ranchi district revealed that the total sulphur content in soils varied widely from 212 to 1841 mg kg^{-1} (Singh *et al.*, 1993).

2.1.3 Adsorbed sulphate

Most surface horizons and light textured soils had only low capacity to adsorb sulphate (Ensminger, 1954). Nearly all the sulphur in the surface horizons of most well drained acid soils is in organic form and only small amounts of sulphate is present (Williams and Steinbergs, 1958).

Sulphate ions are readily absorbed on clay surfaces but it is reversible and concentration dependent (Chao *et al.*, 1962). Montmorillonite has the highest adsorption capacity followed by illite, and kaolinite has the least adsorption capacity (Harward *et al.*, 1962).

Two likely forms of inorganic sulphate in acid soils are, free soluble sulphate and adsorbed sulphate. These two fractions in the soils were extracted by

0.15 per cent $CaCl_2$ and KH_2PO_4 containing 500 ppm P respectively by Williams and Steinbergs (1962) and found that sulphur adsorption was negligible above pH 6.5.

It is reported that KH_2PO_4 is a good extractant for adsorbed sulphate (Williams and Steinbergs, 1964). This extract would include the small amount of soluble sulphate together with the adsorbed. It was also noticed that changes in some soils take place when soils are dried and these can seriously influence the values obtained in the laboratory determination.

Sulphate is firmly adsorbed to iron and aluminium oxides (Aylmore *et al.*, 1967). The higher presence of reactive iron and aluminium in low pH may be the reason for the increased adsorption with decrease in pH (Blair and Nicholson, 1975).

Soil of the tropics generally have low levels of organic sulphur and adsorbed sulphur is often the major reserve of this element. The addition of lime or phosphate to soils decreases sulphate adsorption and may significantly reduce their sulphur status. (Blair *et al.*, 1980).

2.1.4 Organic sulphur

Based on the studies on the chemical nature of sulphate in Australian soils it was reported that for most soils the difference between the total sulphur and sulphate sulphur might give a satisfactory approximation for organic sulphur (Williams and Steinbergs, 1962).

Arora and Takkar (1988) suggested that organic sulphur fraction in the soil can be calculated as the difference between total and sulphate forms extracted by extractants assuming the amounts of reduced inorganic sulphur to be negligible in well drained soils.

In the Kuttanad paddy fields which remains under water for a considerable fallow period in the year the organic sulphur ranged between 225 and 4613 ppm (Mathew, 1989).

2.2 Methods of sulphur estimation (extractants)

Chemical indices of available sulphur should include soluble sulphate in the determination; however any method for which a high degree of correlation with plant response is obtained may be useful, eventhough little is known about the nature of the S determined; usually such methods include soluble sulphate and some unidentified fraction of organic or insoluble inorganic sulphur or both (Bardsley and Lancaster, 1965).

Many procedures have been used to evaluate the sulphur status of soils. Reisenauer (1975) grouped the chemical extractants used in to three types viz. those that remove readily soluble sulphate (eg. water), those that remove readily soluble plus a portion of the adsorbed sulphate (eg. calcium dihydrogen phosphate), those that remove readily soluble and adsorbed sulphate plus a portion of the organic sulphur (eg. 0.3 M $NaH_2PO_4.2H_2O$ in 2 M acetic acid.

Studies conducted by Pal and Motiramani (1971) revealed that there was significant positive correlation between all the methods of S estimation they tried.

2.2.1 Water extractable S

Water is the simplest extractant for sulphate sulphur (Freney, 1958). But there are two disadvantages as reported by Barrow (1961). One disadvantage is that water usually deflocculates the soil thus making extracts difficult to filter. Secondly water extracts sulphur which is not available to plants or micro-organisms.

Although soluble sulphate is readily available to plants, most surface soils contain such small amounts that it is not surprising that some poor correlations have been reported for the relationship between water-soluble sulphate and plant growth (Ensminger and Freney, 1966).

In alluvial rice soils significant correlations of water extractable sulphur with dry matter yield, grain yield and percentage grain yield were obtained by Tiwari *et al.* (1983).

Water extracted more S than salt solutions, the higher concentrations of total extractable sulphur removed by water could not be accounted for by increases in the sulphate sulphur concentration. It could be due to the reason that the H_2O resulted in the dispersion of the organic material and therefore more organic sulphur was probably extracted in the water than in the weak salt extractants (Maynard *et al.*, 1987).

Similar results were also reported by Islam and Bhuiyan (1988), Mehta *et al.* (1988), Sharma *et al.* (1988) and Blair *et al.* (1991).

2.2.2 Sodium chloride extractable S

The NaCl (1%) extractable S in soil was found significantly correlated to uptake of S by no sulphur in a study of Venkateswarlu and Subbiah (1969) to estimate the sulphur status of rice soils of different states. Significant correlations between total uptake of S in plants of control pots with 1 per cent NaCl extractable sulphur were also reported by Pal and Motiramani (1971) and Tisdale (1971).

Available Sulphur in rice soils was extracted by Tiwari *et al.* (1983) using 1 per cent sodium chloride after heating and 1 per cent sodium chloride without heating. They found that the ranges and means of S content in the soils were 7 to 40.2 and 7 to 40.4 and 16.2 and 15.5 ppm respectively for both the extractants. The S content significantly correlated to the dry matter yield without sulphur and percentage grain yield.

Similar results were also reported by Mehta *et al.* (1988) in alluvial soils of Agra, Sharma *et al.* (1988) in Himachal Pradesh and Reddy *et al.* (1993) in Alfisols of Andhra Pradesh.

2.2.3 Ammonium acetate extractable S

Extraction of S using 1N NH_4OAc solution is a good method to assess the availability of organic sulphur (Mc Clung *et al.*, 1959).

Bardsley and Lancaster (1960) observed that the critical level of NH_4OAc extractable S was 30 mg kg^{-1} in wet land soils.

Ammonium acetate is a good extractant as it can overcome the difficulties caused by deflocculation which is seen in the case of extraction with water. However, this procedure extracts some organic matter and this interferes with precipitation of barium sulphate (Barrow, 1967).

Linear correlation coefficients between acetate extractable sulphur and percentage yield and uptake of sulphur were reported by Tisdale (1971).

It is reported that 1N NH_4OAc extractable sulphur was significantly correlated to per cent dry matter yield, leaf S concentration and total S uptake in potato (Singh and Srivastava, 1993).

2.2.4 Calcium chloride extractable sulphur

According to Barrow (1967) a much simpler procedure to estimate available S in soil is to extract the soil with a dilute solution of a salt of divalent cation such as calcium chloride. By this not only clear solutions are obtained but the extraction of non-available sulphur which occurs with water extracts is prevented.

Walker and Doornenbal (1972) compared 0.15 per cent $CaCl_2$ with water for extraction of sulphate sulphur in soils and reported that extraction with $CaCl_2$ was preferred, as calcium flocculated the clay particles, resulting in faster filtering and clearer filtrates than were obtained with water.

In alluvial rice soils of Uttar Pradesh 0.15 per cent $CaCl_2$ gave a mean S content of 11.2 ppm and the values ranged between 3.2 and 27.0 ppm in the 24 samples analysed (Tiwari *et al.*, 1983). Karwasra *et al.* (1986) reported from an investigation of 26 surface soil samples collected from different locations in Haryana that 0.15 per cent $CaCl_2$ was a good extractant in predicting sulphur availability.

Hoque *et al.* (1987) evaluated different methods to assess the adequacy of potential soil S supply to crops and noticed that sulphate extracted with $CaCl_2$ correlated with tissue sulphur concentrations from the plant bioassay technique.

Similar results were also obtained by Mehta *et al.* (1988), Sharma *et al.* (1988) and Reddy *et al.* (1993).

In the Entisols and Vertisols of Gujarat, Misra *et al.* (1990) noted that sulphate sulphur extracted with 0.15 per cent $CaCl_2$ solution varied from traces to 64 ppm S. Taking 10 ppm of $CaCl_2$ extractable S as low, 45 per cent of all the soil sample analysed were likely to be deficient in available S.

In most soils salt solutions such as $CaCl_2$ and LiCl are preferred to water because these solutions keep the soil flocculated and aid filtration of the salt solutions (Anderson *et al.*, 1992).

2.2.5 Bray's extractant extractable S

Venkateswarlu and Subbiah (1969) observed that the sulphur extracted by Bray's reagent showed no significant correlation with uptake of sulphur by no sulphur (control) plants.

Palaskar *et al.* (1981) reported that Bray's No.1 extractant was as efficient as 0.5 M $NaHCO_3$ in extraction of sulphur in acid soils.

However, Palaskar and Ghosh (1982) reported that Bray's solutions had no significant correlation to dry matter yield and S uptake by plants. Similar results were reported by Rahul and Paliwal (1978) and Ramamurthy and Raju (1987).

2.2.6 Ammonium acetate + acetic acid extractable S

An appraisal of some soil test procedures for available sulphur in alluvial soil conducted by Palaskar and Ghosh (1982) showed that ammonium acetate + acetic acid extractant gave significant positive correlation with dry matter yield and sulphur uptake of berseem. In this the critical level of available sulphur had been found to be 32 ppm.

Bansal *et al.* (1983) found significant correlation for relative yield of soyabean to 0.5N NH_4OAc + 0.25N HOAc extractable sulphur and the critical level was found to be 8 ppm.

Analysis of the sulphur content of the acid soils of Karnataka showed that available sulphur content extracted by the acid buffered salt solution - 0.5N NH_4OAc + 0.25N HOAc - ranged from 0.81 to 9.85 ppm (Ananthanarayana *et al.*, 1986).

Islam and Bhuiyan (1988) reported that available sulphur in wet land rice of Bangladesh extracted by NH_4OAc + HOAc varied from 4.5 to 43.8 and the critical concentration was 11 ppm.

Similar results were also obtained by Mehta *et al.* (1988), Sharma *et al.* (1988) and Tiwari *et al.* (1993).

2.2.7 Phosphate extractable S

Sulphur extracted by 500 ppm P was significantly correlated with uptake of S by no sulphur plants (Venkateswarlu and Subbiah, 1969). Soil test values obtained by KH_2PO_4 and $Ca(H_2PO_4)_2$ did not differ significantly. The non-significant differences between the extraction values by phosphate solutions and high correlation between them (r = 0.907) suggested that both these reagents derived the sulphate sulphur from the same pool in soils (Pal and Motiramani, 1971).

Phosphate is the ion most widely used to displace adsorbed sulphate (Ensminger, 1954; Freney and Spencer, 1960). Potassium dihydrogen phosphate has usually been used, but the solutions are dilute and because the cation is monovalent difficulties with filtration can occur (Fox *et al.*, 1964).

The dilute solution of calcium dihydrogen phosphate combines the advantages of calcium chloride with those of phosphate solutions and therefore is a suitable extractant for extraction of sulphur (Barrow, 1967).

The presence of organic matter in 0.01 M $Ca(H_2PO_4)_2$ at pH 4.2 suppressed $BaSO_4$ precipitation and therefore it is suggested to treat this solution with charcoal to remove the organic matter (Sinclair , 1973).

Phosphate solution generally extracted more sulphate sulphur from the acidic soil and less SO_4-S from the alkaline soils than did cold water; SO_4-S extracted by chloride was intermediate (Westermann, 1974).

Wang (1976) reported that 10 mg kg^{-1} of sulphur, extractable by monocalcium method separated deficient from non deficient wet land rice soils of Amazon Basin.

Measuring available sulphur in alluvial soils of Madhya Pradesh, using different soil test methods,Bansal *et al.* (1979) reported that monocalcium phosphate had the best probable relationship with percentage yield and total sulphur uptake in control plants.

Studies for diagnosing sulphur deficiency in Vertisol revealed that relative yield of soyabean and uptake of S from control pots had significant correlations to $Ca(H_2PO_4)_2$ and KH_2PO_4 extractable sulphur and the critical levels for both the extractants were 10 ppm S (Bansal *et al.*, 1983). Similar correlations of KH_2PO_4 and $Ca(H_2PO_4)_2$ extractable sulphur with grain yield and dry matter of rice in control pots were also reported by Tiwari *et al.* (1983), while evaluating alluvial soils of Kanpur.

Islam and Bhuiyan (1988), after evaluation of 9 extractants, suggested $Ca(H_2PO_4)_2$ at 500 ppm P as the most convenient extractant to use because it extracted the highest available sulphur from the soils, gave a clear extract and was easy to handle.

Similar results were obtained by Mehta *et al.* (1988), Sharma *et al.* (1988) and Blair *et al.* (1991).

P solutions extracted higher levels of S than either H_2O or Cl salt solutions in high S adsorbing soils. However this difference was not significant in low S adsorbing soils (Anderson *et al.*, 1992).

Singh *et al.* (1993) postulated that the higher level of adsorbed sulphate (extracted by 0.01 M $Ca(H_2PO_4)_2$ could be due to higher presence of iron and aluminium oxides.

2.2.8 Phosphate + Acetic acid extractable S

Greater amounts of sulphur are extracted when the pH of the solution is adjusted to the pH of the soils which contain high levels of variably charged clay particles (Spencer, 1979).

In a study with the alluvial soils of Delhi, Punjab and Haryana, significant correlations were obtained between dry matter yield and uptake of sulphur by berseem and monocalcium phosphate + acetic acid extractable sulphur; and the critical level of available sulphur was found to be 23 ppm (Palaskar and Ghosh, 1982).

Monocalcium phosphate @ 500 ppm P + 2N HOAc was used to extract available sulphur in 20 surface soil samples of rice growing areas of Dhaka district by Islam and Bhuiyan (1988) and found that the critical concentration for the extractant was 11 ppm S in the Cate and Nelson graphical method.

2.2.9 Morgan's reagent extractable S

Venkateswarlu and Subbiah (1969) observed that S extracted by Morgan's solution in 13 different soils ranged between 19.4 and 87.5 ppm. Evaluation of soil test methods for measuring available sulphur by Pal and Motiramani (1971) showed that correlations were highest for Morgan's reagent with total S uptake and percentage yield and this extractant was suggested to be suitable for determining available sulphur in medium black soils of Jabalpur.

Studies conducted by Tiwari *et al.* (1983) revealed that the range of sulphur extracted with NaOAc + HOAc in 24 samples of surface soil collected from representative alluvial tract of Kanpur district varied from 5 to 37 ppm with a mean value of 14.7 ppm and the extractant had significant correlation with percentage dry matter yield. The NaOAc + HOAc extractable S was also correlated significantly to grain and straw yield.

Sulphur status of soils of different agroclimatic regions of Haryana was investigated by Karwasra *et al.* (1986) and observed that Morgan's reagent provided good index of sulphur availability in these soils.

Similar results were also reported by Islam and Bhuiyan (1988), Mehta *et al.* (1988), Sharma *et al.* (1988).

2.2.10 Olsen's reagent extractable S

Alkaline extraction of soils with $NaHCO_3$ is effective in solubilising and replacing anions as well as some organic fractions. Values obtained with this method generally account for more S than is present as acetate soluble sulphate in most soils and probably include both organic and inorganic S to some extent (Bardsley and Lancaster, 1965).

Soil organic sulphur has been extracted with alkaline solutions of NaOH and 0.5 M $NaHCO_3$ at pH 8.5 (Williams and Steinbergs, 1964 and Rehm and Caldwell, 1968).

The alkalinity of $NaHCO_3$ solution is the agent responsible for hydrolysing the soil organic sulphur so that at higher pH more soil organic sulphur was extracted (Kimler and Nearpass, 1960).

In a comparison of five methods for determining the sulphur status of soils, Cooper (1968) observed that the $NaHCO_3$ solution extracted a great deal of organic matter indicated by dark coloured filtrates, as well as sulphate from the clay by virtue of its high pH, and the response level was found to be 30 ppm.

Therefore, $NaHCO_3$ method extracts S from both adsorbed SO_4 and fraction of soil organic sulphur. The level of sulphur extracted is 1.1 to 5.6 times greater than the amount extracted by the phosphate solutions (Probert, 1976 and Rehm and Caldwell, 1968).

Tiwari *et al.* (1983) evaluated nine soil test methods for diagnosing sulphur deficiency in rice in alluvial soils of Uttar Pradesh and found that the 0.5 M $NaHCO_3$ extracted sulphur showed the highest correlation with grain yield of plants grown without sulphur.

Sodium bicarbonate (0.5 M) was successfully tried for extraction of sulphur by Islam and Bhuiyan (1988), Mehta *et al.* (1988), Sharma *et al.* (1988) and Blair *et al.* (1991).

Mahato *et al.* (1992) studied the available sulphur status in Chotanagpur region of Bihar and inferred that the extraction of available sulphur by $NaHCO_3$ varied based on soil reaction and the average values under acidic, neutral and alkaline reaction were 11.9, 13.4 and 17.0 ppm respectively.

2.2.11 Ammonium chloride extractable S

Extraction and determination of sulphur in organic horizons of forest soils by Maynard *et al.* (1987) revealed that 0.01 M NH_4Cl extractant was found to be the most consistent extractant. It was seen that in all cases of samples 0.01 M NH_4Cl removed significantly less total extractable sulphur than water but significantly higher concentration than $CaCl_2$.

2.3.1 Correlation of sulphur extracted by different reagents with plant growth

Soil and plant tests for available sulphur in wet land soils was studied by Islam and Ponnamperuma (1982) and observed that all the four methods gave a significant correlation with grain yield. However only calcium phosphate and ammonium acetate extractable sulphur significantly correlated with the total sulphur content of the shoot.

Tiwari *et al.* (1983) found high degree of correlation of extractable sulphur with percentage yield in grain and straw. Sulphur concentrations in various parts of rice plants receiving no sulphur treatment showed poor correlation with dry matter production and yield of grain and straw.

Soil available S determined by phosphates, Morgans' extractant and Olsens' reagent were positively correlated at 1 per cent level with dry matter yield and total sulphur content of rice (Islam and Bhuiyan, 1988).

2.3.2 Relationship of soil sulphur status with soil parameters

Highly significant positive linear correlation between total and organic sulphur with organic carbon has been reported by Lande *et al.*, 1977 in Maharashtra soils. They further observed that there was negative correlation between pH and sulphate sulphur. However, Patil *et al.* (1981) reported positive correlation between different forms of sulphur and pH in the soils of the same state.

From the studies on available sulphur in wet land rice soils, Islam and Ponnamperuma (1982) observed that submergence lowered soil solution Eh within a week. Sulphate concentrations in most of the soil solutions decreased to a level of 1 to 8 mg l^{-1} within 8 weeks of submergence.

Balanagoudar and Sathyanarayana (1990) studied the relationship of different soil properties and different forms of sulphur in soils of North Karnataka and found that both water soluble and sulphate sulphur were positively correlated with pH, EC, $CaCO_3$ and clay content.

In the Entisols and Vertisols of Orissa, Misra *et al.* (1990) observed significant correlations of total sulphur with clay and organic carbon content of the soils.

Patgiri and Baruah (1993) observed positive highly significant correlation between sulphur availability and organic carbon content of soil.

2.4.1 Crop response to sulphur application

Response to S fertilization are most commonly obtained in areas of low atmospheric S accretions, on strongly leached soils or on soils exhibiting minimal surface adsorption (Harward and Reisenauer, 1966).

Chlorosis in paddy seedlings leading to premature mortality in the calcareous soils of Udaipur was very effectively controlled by sulphur application. The levels of 750 kg S ha^{-1} gave highest rate of seedling production per m^2 (Singh and Gupta, 1968).

Blair *et al.* (1979) reported progressive and significant increase in number of panicles per plant from 4.1 to 14.9 when the S nutrition was increased from 0 to 80 kg ha^{-1}. They have further observed that the total dry matter yield and grain yield of rice increased significantly with S levels up to 80 kg S ha^{-1}.

Spencer and Freney (1980) reported that grain yield responses at maturity parallelled vegetative responses. Only when nitrogen was added there was a significant grain response to sulphur addition, and only when S was added did nitrogen additions result in a significant increase.

Chandrasekharan (1987) observed that in ill drained soils, incorporation of large amount of organic manures inhibited the rice growth due to formation of propionate and butyrate in soils, and reduced the yield. Sulphate was observed to arrest these formation of injurious substances.

Ramanathan and Saravanan (1987) reported that sulphur application increased rice yield by 8 to 15 per cent over the yield by nitrogen fertilizer alone.

Gupta and O'toole (1986) reported that in upland rice sulphur application at the rate 20 ppm increased the growth, dry matter content and yield of IR 20 rice.

In the alluvial soils of Punjab an increase in wheat yield by 186 per cent over control in response of application of 18 kg sulphur per hectare has been reported (Manickam, 1987).

Studies on long term effect of intensive rice cultivation and fertilizer use on sulphur availability to rice in Inceptisols of Orissa during 1971-75 showed that there was decline in yield with application of S-free NPK fertilizers and the study indicated that 44 kg S ha^{-1} in a cropping cycle would be necessary for maintaining the sulphur status of the soil (Sahoo and Panda, 1987).

Addition of 50 kg S ha^{-1} as ammonium phosphate is reported to have increased the yield of rice from 2730 kg to 3700 kg per ha simultaneously increasing the straw yield by 27 per cent (Vijayachandran, 1987).

Pot culture studies with rice conducted by Ahmed *et al.* (1988) revealed that there was significant and linear increase in yield of rice straw upto 60 kg S ha^{-1}. However grain yield was highest (49.758 pot^{-1}) at 30 kg S ha^{-1}. It was further noticed the grain to straw ratio significantly increased by S application.

The dry matter yield of shoot increased by 47.1 per cent in soils with sulphur application where total sulphur in plant was less than 0.13 per cent (Islam and Buiyan, 1988).

George (1989) found that S application increased LAI, dry matter production and yield contributory factors like number of productive tillers per hill, panicle length, number of grains per panicle and 1000 grain weight.

In the rice-rice cropping system at Bhubaneswar 40 kg S ha^{-1} applied annually was found necessary to maintain optimum S level in soil and to sustain high productivity of the cropping system (De Datta *et al.*, 1990).

Evaluation of data from field experiments conducted during pre and post high yielding varieties era in various states showed the superiority of AS and demonstrations with AS increased yield up to 53 per cent (Prasad, 1990).

The FAO interregional sulphur network trials showed that out of 120 sites where the trials were conducted in India, response to sulphur was significant in 67 locations (Roy, 1991).

Rice grain yield and straw yield were increased by 1084 kg ha^{-1} and 1075 kg ha^{-1} respectively when sulphur was added in the form of APS @ 37.5 kg S ha^{-1} to NPK fertilization. In the same experiment the source of ammonium sulphate gave a rise in yield of grain and straw by 994 kg and 1173 kg ha^{-1} respectively (Clarson and Ramaswamy, 1992).

2.4.2 S content and critical levels in plant

Plant composition can be used as a measure to assess sulphur deficiency. Freney *et al.* (1962) suggested the critical levels of sulphur for cotton and lucerne as 0.20 per cent and for clover and grasses as 0.26 per cent.

In cereals there is a general decline in the sulphur content of the tops with age. Yoshida and Chaudhry (1979) reported that the sulphur content of IR-8 rice declined from 0.26 per cent two weeks after planting to 0.11 per cent at flowering.

Osiname and Kang (1975) found that the critical levels of sulphur content in rice grains and straw were 0.12 and 0.1 per cent respectively. They also observed that during vegetative phase and flowering period the critical level was as high as 0.16 per cent.

Similarly, Yoshida and Chaudhry (1979) reported that the critical sulphur content in straw for the maximum dry weight varied from 0.16 per cent at tillering stage to 0.06 per cent at maturity.

Sulphur contents of the rice grain vary from 0.034 per cent under deficiency conditions to 0.16 per cent in a non responsive situation and rice grain yields may vary from 0.75 to 8 t ha^{-1} (Blair *et al.*, 1980).

In another study on rice, the critical limits of total plant sulphur were 0.16 per cent in the shoot and 0.06 per cent in the straw at harvest (Islam and Ponnamperuma, 1982). Critical level of S in wheat was observed to be 0.18 per cent in the Vertisol of Jabalpur region (Bansal, 1992).

Long term effect of intensive cropping and fertilizer use on sulphur availability to rice in an Inceptisol in Orissa showed 44 kg S ha^{-1} per cropping cycle would be necessary to maintain the sulphur status (Sahoo and Panda, 1987).

Studies on the adequate nutrient ranges in rice showed that both critical and adequate levels of S content at tiller stage ranged from 0.17 to 0.22 per cent and 0.23 to 0.32 per cent respectively. At flag leaf stage these values got reduced to 0.09 and 0.09 to 0.14 per cent (Brar *et al.*, 1982).

Manchanda *et al.* (1987) reported that total sulphur content in rice plants increased by 21 to 43 per cent over control with sulphur application. A maximum of 0.094 per cent total S was recorded in plants where 20 ppm sulphur was applied.

The leaf S in rice plants grown in Entisols and Inceptisols of Ludhiana varied from 0.11 to 0.25 per cent with an average of 0.17 per cent (Arora and Takkar, 1988).

2.4.3 Response of rice to sources of S

In experiments of rice, responses to fertilizers such as ammonium sulphate, potassium sulphate, zinc sulphate and super phosphate were attributed to be their nitrogen, potassium, zinc or phosphorus contents and the potential response of sulphur was ignored (Blair *et al.*, 1978).

Studies conducted at Atomic Energy Commission Farm, Dhaka with different sources of sulphur on rice under submerged conditions revealed that sulphur applications improved yield and sulphur content of plants and available sulphur in the soil. Further the performance of different sources of sulphur showed that ammonium sulphate was superior to elemental sulphur, gypsum and sulphur coated urea (Alam *et al.*, 1985).

George (1989) observed that both ammonium sulphate and ammonium phosphate sulphate were superior sources of S for rice compared to elemental sulphur.

The effect of sources and rates of sulphur on flooded soil rice yields illustrated by Ismunadji (1991) shows that ammonium sulphate at levels of 8 kg and 32 kg S ha^{-1} significantly out yielded the yields produced with the same dose of sulphur by the sources gypsum, elemental S, urea-S and S-bentonite. However, Mamaril *et al.* (1991) reported that urea-S was the superior source and ammonium sulphate was on par with it.

Reviewing the results of the FAO interregional sulphur network, Roy (1991) reported that compared to gypsum, ammonium sulphate was found to be a superior source for supplying sulphur to rice.

Green house investigations regarding the effect of different sulphur carriers on dry matter yield and sulphur uptake in maize and wheat in Punjab clearly showed the superiority of $(NH_4)_2SO_4$ over other sulphur carriers like, elemental sulphur, super phosphate, gypsum and pyrite (Singh and Chibba, 1991).

Studies conducted at TNAU to evaluate the performance of 14 sources of fertilizers, with and without S application, showed that ammonium phosphate sulphate was superior to others and was followed by ammonium sulphate (Clarson and Ramaswamy, 1992).

Tiwari *et al.* (1992) compiled the results of the FAO's International Sulphur Research Network Trials and reported that 20 kg sulphur applied as $(NH_4)_2SO_4$ gave higher yield of wheat than 30 kg S ha^{-1} applied as gypsum. Further the residual effect of $(NH_4)_2SO_4$ was higher than that of gypsum in the second crop of rice.

2.4.4 Effect of sulphur on nutrient uptake

Application of sulphur was found to significantly increase total N and protein and N content of alfalfa in the study conducted on the nitrogen-sulphur relations (Aulakh *et al.*, 1976). The large reduction in the nonprotein nitrogen fractions (nitrate, amide and amino acid N) obtained indicated that S application accelerated the metabolic pathway of protein synthesis in the plant.

Marok and Dev (1980) reported that in wheat sulphur levels upto 50 ppm increased the sulphur content, P content and uptake of S. The sulphur content rose from 0.101 to 0.230 per cent and the S removal from 8.1 to 18.9 kg S ha^{-1}.

Sachdev *et al.* (1982) reported that application of gypsum significantly increased N and S content as well as N and S uptake.

George (1989) studied the effect of AS, APS and elemental sulphur in rice and opined that nitrogen content and uptake of S were significantly increased by S nutrition compared to control. She observed that uptake of S nearly doubled (i.e. from 8.7 kg to 16.8 kg S per ha) by application of 60 kg S ha^{-1}.

Singh *et al.* (1990) found that sulphur application increased the availability of N, P, K, Ca and Mg in groundnut.

When S became limiting non-protein N increased; application of S resulted in an increase in total as well as non-protein S and total and protein N contents (Bansal, 1992).

Studies at Coimbatore revealed that under APS and AS fertilization @ 37.5 kg S ha^{-1} rice crop removed 42.7 kg and 37.3 kg S ha^{-1}, respectively and were significantly superior to elemental sulphur applied in combination with various NPK sources (Clarson and Ramaswamy, 1992).

2.4.5 Influence of sulphur on rice quality

Studies on the role of sulphur in grain quality showed that application of sulphur increased the protein content of paddy and wheat grains (Das and Datta, 1973).

Nanavathi *et al.* (1973) found that the content of chlorophyll, water soluble protein and peroxidase in rice were significantly reduced under conditions of sulphur deficiency.

Sulphur is an essential constituent of amino acids cystine, cysteine and methionine which are important in protein formation, structure and function (Blair *et al.*, 1978).

Ismunadji and Miyake (1982) found from pot culture experiments that application of S in various sources increased cystine and methionine content of brown rice along with significant enhancement of grain yield.

Protein content of rice increased from 8.15 per cent to 11.31 per cent when the rice crop was supplied with 30 kg S per ha. Increase was also observed in the case of total essential amino acids which raised from 3,643 to 4,412 mg per 100 g flour (Kanwar, 1984).

Increase in the protein content in rice by sulphur application from 3 to 8.8 per cent is reported from TNAU (Clarson and Ramaswamy, 1992).

2.4.6. Interaction of sulphur with other nutrient elements

A study on the direct and residual effects of sulphates and phosphates in crop production using ^{32}S revealed that there was significant interaction between the two nutrients and the highest yields were obtained at S application @ 20 ppm and P @ 40 ppm (Venkateswarlu, 1971).

The relationship between sulphur and zinc has been reported to be antagonistic in groundnut (Shukla and Prasad, 1979). However it was reported as synergetic in soyabean (Kumar and Singh, 1980) and Mustard (Sharma *et al.*, 1989).

The availability of S to plants depend on its interaction with other nutrient elements present in the soil in addition to soil factors. N, P, K, Ca, Mg, Zn, Mo and Se interact with S in absorption and utilization (Singh, 1986).

Investigations on the effect of sulphur on manganese and copper nutrition of canola (*Brassico napus* L.) by Karamanos *et al.* (1989) revealed that there was progressive increase in the concentration and uptake of copper by graded levels of S application upto 20 kg S ha^{-1}.

Aulakh *et al.* (1990) found that sulphur upto 40 kg S ha^{-1} interacted synergetically with P and resulted in increased seed yield and enhanced protein and oil synthesis.

Field experiments with sunflower conducted by Gangadhara *et al.* (1990) at Dharward revealed that in sunflower foliage there was progressive increase in the concentration of SO_4-S, B, Zn and Fe with higher levels of sulphur but the concentration of Mn and Cu decreased when the level was above 5 kg S per ha.

The presence of abundant sulphate in the root zone typically reduces the selenium concentration in plants. The reduction in the toxic concentrations of selenium can result from antagonistic interactions between Se and SO_4 in uptake or may simply reflect a dilution of plant selenium due to increased plant growth in S application (Jacubs, 1989).

However, antagonism was present only at sufficient sulphate in soil and a synergistic interaction between selenium and sulphur occurred in rice and barley at low levels of sulphur (Mikkelsen and Wan, 1990).

Studies with ^{15}N and ^{35}S revealed that there synergetic effect to these nutrients on dry matter yield and uptake of N and S (Sachdev and Deb, 1990).

Sharma *et al.* (1990) found that higher levels of zinc and sulphur (10 ppm and 80 ppm respectively) progressively increased seed yield in mustard.

The sulphur requirement of plants depends on the balance between S and other nutrient elements as there may be synergistic or antagonistic effect of one on the other (Tiwari, 1990).

Khandar and Shinde (1991) observed that sulphur levels progressively increased P content and uptake of P in black gram.

Green house studies to investigate the effects of S and Zn on yield and their uptake in rice conducted by Mukhi and Shukla (1991) showed that application of 25 ppm S alone or with Zn increase biomass yield of rice, but at higher levels of both these nutrients the biomass yield decreased.

Bansal (1992) observed that, total and protein nitrogen content increased in wheat with application of sulphur.

2.5 Sulphur use efficiency

In a study on an acid soil with high organic matter content ^{35}S labelled gypsum gave significant increase in dry matter production. The sulphur utilization varied from 10 to 57 per cent and the highest was at 20 ppm (Venkateswarlu, 1971).

Dhillon and Dev (1978) observed that sulphur utilization percentage increased when the application was raised upto 10 ppm but the higher levels (20 ppm) decreased it. They further reported that sulphur derived from the fertilizer increased significantly with its higher doses.

A study on the parameters of radio assay showed that sulphur levels upto 50 ppm increased total S uptake and sdff but the utilization percentage of applied sulphur was decreased (Marok and Dev, 1980).

Utilization of sulphur by rice from gypsum using ^{35}S was attempted by Sachdev *et al.* (1982) in a green house experiment. They observed that the sulphur application increased the dry matter yield, nitrogen and sulphur uptake. Nearly 90 per cent of the applied sulphur was recovered in plant and soil. Most of the residual S in soil was in organic fraction, and less than 10 per cent of the applied gypsum sulphur was present as sulphate after harvest.

Experiments conducted at IARI with sulphur application at different levels of tagged sulphur up to 90 kg S ha^{-1} showed that sdff increased while percentage S utilization declined significantly with increase in the applied sulphur to mustard and pea (Sharma and Kamath, 1991).

Tracer studies on sulphur nutrition of black gram and green gram at TNAU showed that the sulphur derived from fertilizer varied from 3.6 to 10.8 per cent. While the fertilizer use efficiency was more or less uniform indicating that the plant requirement was more than the highest level of sulphur tried in this experiment (Subramanian *et al.*, 1991).

Clarson and Ramaswamy (1992) reported that per cent sulphur use efficiency of ammonium phosphate sulphate was highest among the various sources of S studied and APS was closely followed by ammonium sulphate.

George *et al.* (1992) observed significant variation in specific activities of different plant parts. The specific activity was highest in grain compared to other plant parts.

Sreemannarayana and Raju (1994) studied S use efficiency in sunflower using ^{35}S labelled sources under conditions of S deficient soils and concluded that the ratio of S uptake by native and applied sources indicated preferentical absorption of soil sulphur at all levels of applied S upto the highest level of 60 kg S ha^{-1}.

2.5.1 A value

Nearpass *et al.* (1961) found that growth responses from S were related to A value S in soil. Kilmer and Nearpass (1960) reported that A values were correlated with S extracted by sodium bicarbonate.

A values were correlated to per cent S in the control plants and that the critical value for total S in the plant, was related to the critical A value (Nearpass *et al.*, 1961, Harward *et al.*, 1962, Ensminger and Freney, 1966).

The native soil available sulphur as measured by isotopic dilution technique (A values) varied in locations from 95.45 and 276.90 ppm S, and A values correlated at 1 per cent level with the uptake of sulphur (Venkateswarlu and Subbiah, 1969).

Relative contributions of soil applied sulphur in a single basal or in two split doses towards total uptake by flooded rice were studied in pot culture employing ^{35}S labelling technique by George *et al.* (1992). They found that A values vary with the rate of S application.

2.6 Residual effects of S fertilization

The FAO Sulphur Research Network Trials conducted in India during 1987-89 revealed that no residual effect of S to succeeding crop was seen when rice was grown in the same plots where sulphur was applied at graded levels upto 30 kg S ha^{-1} in the *Kharif* season. However there was significant cumulative effect of S application when applied to *Rabi* crop also (Tiwari *et al.*, 1992).

Sachdev *et al.* (1982) reported that most of the residual S in soil was in organic fraction and less than 10 per cent of the applied sulphur was present as sulphate after harvest.

Pot culture trials conducted to evaluate the residual effect of S by Ahmed *et al.* (1989) showed that higher levels of S upto 60 ppm increased the grain yield and straw yield of succeeding rice crop over the lower levels of S.

However, Karamanos and Janzen (1991) reported that very little significant residual benefit of any sulphatic fertilizers from 3 years after application was observed even though, the application levels were as high as 60 and 120 kg S ha^{-1}.

Sulphur balance in soils as influenced by sulphur carriers and crops was studied by Clarson and Ramaswami (1992a) and came to the conclusion that the high losses of total sulphur (unaccounted) through various means in the soils where sulphur was not supplied, stressed the necessity of S nutrition to each crop in order to replenish the depletion of S from the soil to sustain S fertility of the soil. Among the sulphur carriers generally the losses were higher for AS > ES > APS which indicated the superiority of APS.

2.7 Economics of S application

There are no established norms to fix the price of fertilizer sulphur because its presence in fertilizers is either ignored or taken to be as incidental nature tied up with the manufacturing process (Tandon, 1986).

Dev and Sharma (1988) reviewed the research work done on sulphur fertilization in India and reported that response and value cost ratio for rice was the highest compared to other cereals.

Tandon (1991) reviewed 23 studies in rice and concluded that addition of 1 kg S to rice increased rice yield by 16.6 kg.

In a study at TNAU, Coimbatore, it was seen that the application of S @ 37.5 kg ha^{-1} as APS and AS increased the total value of produce to Rs.12475/- and Rs.12140/- respectively from Rs.7871/- of control (Clarson and Ramaswamy, 1992).

Materials and Methods

3. MATERIALS AND METHODS

A series of investigations were carried out with the objectives to assess the status and availability of Sulphur in the major paddy soils (alluvial and brown hydromorphic) of Kerala, to identify an appropriate soil test procedure for estimating available sulphur, to determine critical levels of sulphur, to assess the response of rice to two common sulphatic fertilizers produced in the State and to assess the sulphur use efficiency of rice. The experiments were taken up in four parts to achieve the objectives. The research project was taken up at College of Horticulture, Kerala Agricultural University, Vellanikkara during 1990 to 1994.

3.1 Part-I. Assessment of the sulphur status of rice soils of Kerala

This part of the study was intended to assess the sulphur status of two main rice soils in the State, viz. alluvial and brown hydromorphic soils.

3.1.1 Alluvial rice soil

This comprises 3 types of soils with the nomenclature of coastal alluvium, riverine alluvium and greyish Onattukara (Anon, 1978 and Anon, 1984). The texture of coastal alluvium soils vary from sandy loams to almost sandy. They are slightly acidic in reaction and extremely deficient in all major plant nutrients and organic matter. Riverine alluviums are the true alluvial soils developed from the silt deposits on the banks of rivers and their tributaries. These soils occur on the flood plains and are young productive soils with very little horizon development. They respond well to good management practices. Greyish Onattukara soils are alluvial soils developed on the marine deposits. The soils are coarse textured with immature profiles. They are acidic in reaction and low in fertility. The organic matter status is also low.

The alluvial soils belong to the order Entisols (Anon, 1984 and Johnson, 1980).

3.1.2 Brown Hydromorphic rice soil

These soils occur mostly in the valley bottoms between undulating topography in the midland and low lying valley portions of the highlands. They are often refered to as ground water laterites and ribbon valley laterites. They are colluvio-alluvium and have been formed as a result of transportation and sedimentation of materials from the adjoining highland areas. Wide variations are exhibited in physico-chemical properties and morphological features. In most cases the water table is high. Impeded drainage conditions play an important role in profile development. The soils exhibit characteristic hydromorphic features like organic matter deposition, occurrance of gravel and laterite within the profiles and thereby indicate colluvial soil formation (Gopalaswamy, 1983). The soils belong to the order Inceptisols (Anon, 1984 and Johnson, 1980).

Samples were collected from the above mentioned soils in 10 major rice growing districts in the State in proportionate to the total area under rice (Appendix-I). A total of 210 samples were collected one each from a different padasekharam or a group of cultivated fields in a location. The number of samples collected from different districts are mentioned here under:

District	Number of samples		
	Alluvial	Brown hydromorphic	Total
1. Palakkad	29	25	54
2. Thrissur	21	11	32
3. Ernakulam	4	19	23
4. Alappuzha	19	6	25
5. Malappuram	18	7	25
6. Kottayam	3	8	11
7. Kollam	2	13	15
8. Thiruvananthapuram	5	6	11
9. Kannur	4	7	11
10. Kozhikkode	–	3	3
Total	105	105	210

The various locations are listed in Appendices I(a) and I(b).

3.1.3 Collection of samples

In each padasekharam or group of rice fields in one location composite samples were taken. Soil was collected from different sites. A 'V' shaped cut was made upto 20 cm depth and a slanting slice to a thickness of 5 cm was collected. These samples were pooled, mixed and a composite sample of about 1 kg was drawn, after quartering method, in polythene bags. The soil samples collected were air dried, gently crushed with a wooden mallet, sieved through 2 mm sieve and stored in polythene bags.

3.1.4 Analysis of samples

The samples collected were extracted with two extractants viz. 0.15 per cent $CaCl_2$ and 500 ppm P(KH_2PO_4). A quantity of 20 g soil was weighed out in to a 250 ml conical flask, 100 ml of 0.15 per cent $CaCl_2$ was added and then shaken for 1 hour. The suspension was then filtered through Whatman No.42 filter paper. A 10 ml aliquot was transferred to 25 ml volumetric flask, added 1 ml gum acacia (0.25% solution) and turbidity was then developed with 1 g (cup measure) of 30 to 60 mesh sized $BaCl_2$ crystals. Turbidity readings were taken immediately in spectronic 20 D at 440 nm and S content estimated as suggested by Chesnin and Yien (1950) and Jackson (1958). The sulphur content extracted by $CaCl_2$ is presented as soluble sulphate sulphur as suggested by Singh *et al.* (1993).

A similar extraction with 500 ppm P solution (of KH_2PO_4) was made. The extract was treated with activated charcoal and filtered to remove the organic matter and to get a clear solution. Turbidimetric reading was made as mentioned above. Adsorbed sulphate was calculated by deducting the calcium chloride extractable sulphur from phosphate extractable sulphur as suggested by Arora and Takkar (1988) and Singh *et al.* (1993). Total sulphur was estimated by oxidising sulphur to sulphate by the method suggested by FAO (1988) followed by Turbidimetric determination (Chesnin and Yien, 1950). Organic sulphur was computed as the difference between total sulphur and phosphate extractable sulphur. The sulphur status of the soils sampled are tabulated and presented. The analytical data on S content, organic carbon and pH are furnished in Appendix IIa and Appendix IIb.

The samples were grouped in to low, medium and high in available S concentration for delineation of the sulphur status in the rice soils under study. The mean values and ranges of different forms of sulphur are presented for both types of rice soils.

3.2 Part-II. Identification of suitable soil text procedure for estimation of available sulphur

This part of the study was intended to determine the critical levels of sulphur in the alluvial and brown hydromorphic soils. A total of 60 locations (30 each under the two soil types) which gave a range in available sulphur from low to high status were selected. The lists of locations are given in Appendices III and IV. The soil samples collected from these locations approximately 40 kg each in clean polythene gunny bags were processed as mentioned in 3.1.3. One kg each of the soil sample was separatly transferred in containers for analysis. These samples were analysed for available sulphur employing several extractants.

3.2.1 The extractants used were:

1)	Water (Distilled)	- (Freney, 1958)
2)	1% NaCl after heating	- (Williams and Steinbergs, 1959)
3)	NH_4OAc (1N)	- (Mc Clung *et al.*, 1959)
4)	0.15% $CaCl_2$	- (Williams and Steinbergs, 1959)
5)	0.3 N NH_4F + 0.25 N HCl (Brays')	- (Palaskar and Ghosh, 1982)
6)	0.5 N NH_4OAc + 0.25 N HOAc	- (Bardsley and Kilmer, 1963)
7)	500 ppm P as $Ca(H_2PO_4)_2$	- (Fox *et al.*, 1964)
8)	500 ppm P as KH_2PO_4	- (Ensminger, 1954)
9)	500 ppm P as $Ca(H_2PO_4)_2$ + HOAc(1N)	- (Palaskar and Ghosh, 1982)
10)	NaOAc + HOAc (Morgan's)	- (Anderson and Webster, 1959)
11)	0.5 N $NaHCO_3$ (Olsen's)	- (Kilmer and Nearpass, 1960)
12)	0.1 M NH_4Cl	- (Maynard *et al.*, 1987)

The procedure followed for analysis was as in 3.1.4 except that the shaking time was standardised as 30 minutes. The turbidity was measured by UV-VIS-Spectrophotometer.

3.2.2 Pot culture

The pot culture was conducted at the glass house of Radio Tracer Laboratory, Vellanikkara. The soil samples collected from the 60 locations (30 each from alluvial and brown hydromorphic soil) as shown in 3.2 was used for the pot culture. Each soil was weighed and transfered @ 5 kg each to 4 plastic pots. These 4 pots were used for two treatments viz. S_0 (without sulphur) and S_{40} (with 40 kg sulphur per ha) with two replications. The pots were labelled to indicate the location number, treatment and the replication number.

3.2.3 Seeds and sowing

Rice variety *Jyothi* (Ptb-39) with parentage Ptb-10 x IR-8 was used for the experiments. The seeds were pre-soaked for 12 hours and incubated for 48 hours. Sowing of sprouted seeds was done @ 12 seeds per pot and 9 seedlings were retained removing the excess after the 6th day.

3.2.4 Fertilizer application and treatment

N, P_2O_5 and K_2O were applied @ 90:45:45 kg ha^{-1} (Anon, 1993). The nutrients were applied by LR/AR grade chemicals. Nitrogen and sulphur were supplied as urea and ammonium sulphate in control and S treated pots so as to supply 0 kg and 40 kg S respectively. P and K were applied as KH_2PO_4 and KCl (AR grade)

3.2.5 Plant protection

Pest surveillance was made and phophylactic measures were taken up. Phosphamidon was sprayed to the crop 4 times to protect the crop from thrips and stem borer.

3.2.6 Harvest and post harvest

The plants were harvested after recording biometric observations. Grain and straw of the plants in each pot were, dried and weights recorded.

3.2.7 Chemical analysis of plant samples

The grain and straw were dried in paper covers under sun and oven dried at 70°C. After recording the weights the samples were ground. One gram each of the samples was weighed in to 150 ml conical flask, digested using 2:1 mixture of HNO_3 + $HClO_4$ @ 15 ml per sample. After over night digestion in room temperature the sample flasks were heated on hot plate. The plant sample extract was made up to 100 ml and kept to settle the silicates. This extract was used for analysing total plant sulphur by turbidimetry. Nitrogen was estimated by microkjeldahl method; phosphorus and potassium content of the plant samples were estimated from the plant extracts using spectronic 20 D. Calcium, magnesium, manganese, zinc and copper contents were estimated using Perkin-Elmer Atomic Absorption Spectrophotometer.

Coefficients of correlations were worked out between available sulphur in the soils as estimated by different methods (3.2.1). Critical levels of sulphur in the two soils viz. alluvial and brown hydromorphic, were determined for different soil test procedures based on the relationship between relative yield and available sulphur content (Cate and Nelson, 1965). Relative grain yield, relative straw yield, relative yield of total biomass and relative uptake of sulphur were worked out for various soils, from the parameters - grain yield, straw yield, total biomass and sulphur uptake - by rice in pot culture using the following formula.

$$\text{Relative yield(\%)} = \frac{\text{Yield in pot without sulphur } (S_0)}{\text{Yield in pot with sulphur } (S_{40})} \times 100$$

Coefficients of correlation between soil test values by different extractions and relative yields were worked for both soil types. Available sulphur extracted by different soil test procedure and relative yields of grain, straw and biomass and sulphur uptake were plotted in scatter diagram and critical levels worked out following Cate and Nelson procedure. Identification of suitable soil test procedure was made as suggested by Bansal *et al.* (1979) and Islam and Bhuiyan (1988).

Many of the pots with no sulphur (S_0) treatment contained green algal growth. A scoring of green algal growth was taken up in S_0 pots and its correlation with S content of soil was studied after $\sqrt{x+1}$ and presented. The relative yield of grain and the sulphur content of plant at harvest for both the soil types have been plotted in scatter diagrams taking sulphur content in X-axis and relative yield in Y-axis. The critical level of sulphur in plant has been worked out using Cate and Nelson procedure.

3.3 Part-III. Response of rice to different levels and sources of sulphur

From the Part-II, two locations identified as low in available sulphates one each belonging to alluvial soil (Cropping System Research Centre, Karamana) and brown hydromorphic soil (Regional Agricultural Research Station, Pattambi) were selected to conduct field experiments to study the response of rice to sulphatic fertilizers. The physico-chemical properties of the experimental fields are presented in Appendix VII. The weather data during the experimental season is presented in Appendix VIII. About 250 kg soil was collected from these two locations for Part-IV of the studies. Field experiments were conducted in these two locations during two cropping seasons viz. *Kharif* and *Rabi* 1992-93. The field experiments of *Rabi* were conducted in separate plots adjacent to plots of *Kharif* experiments. During *Rabi*, rice was cultivated in the plots of *Kharif* experiments without dismantling the bunds to study the residual effect of sulphur application on the succeeding crop.

3.3.1 Treatments

T_1 - Control (S_0)

T_2 - Ammonium sulphate @ 10 kg S ha^{-1} (S_{10}AS)

T_3 - Ammonium sulphate @ 20 kg S ha^{-1} (S_{20}AS)

T_4 - Ammonium sulphate @ 30 kg S ha^{-1} (S_{30}AS)

T_5 - Ammonium sulphate @ 40 kg S ha^{-1} (S_{40}AS)

T_6 - Ammonium phosphate sulphate @ 10 kg S ha^{-1} (S_{10}APS)

T_7 - Ammonium phosphate sulphate @ 20 kg S ha^{-1} (S_{20}APS)

T_8 - Ammonium phosphate sulphate @ 30 kg S ha^{-1} (S_{30}APS)

T_9 - Ammonium phosphate sulphate @ 40 kg S ha^{-1} (S_{40}APS)

Fig.1. Layout plan of field experiments

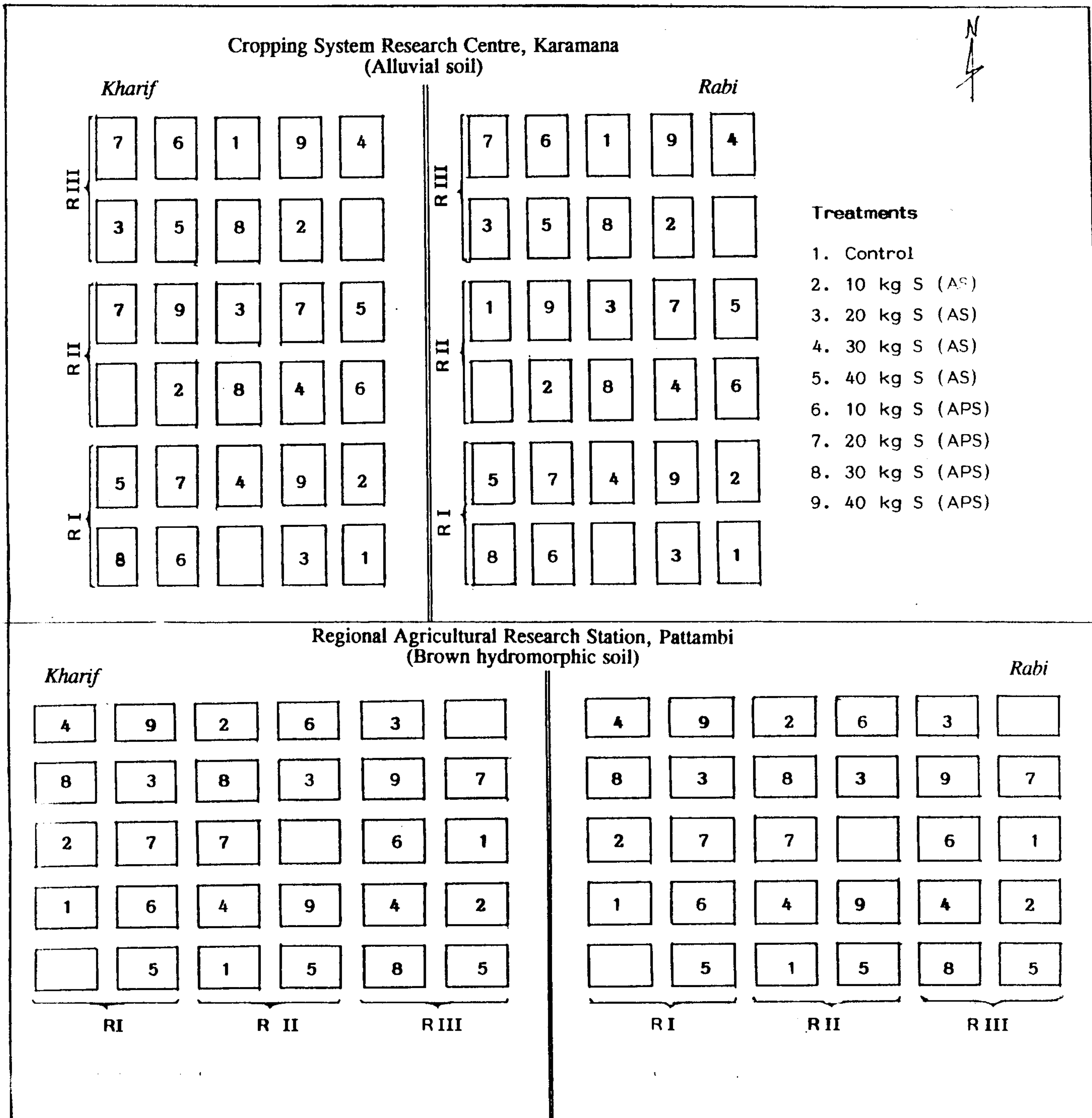


Fig.2(a) **WEATHER DURING THE EXPERIMENT PERIOD AT CSRC, KARAMANA (1992-93)**

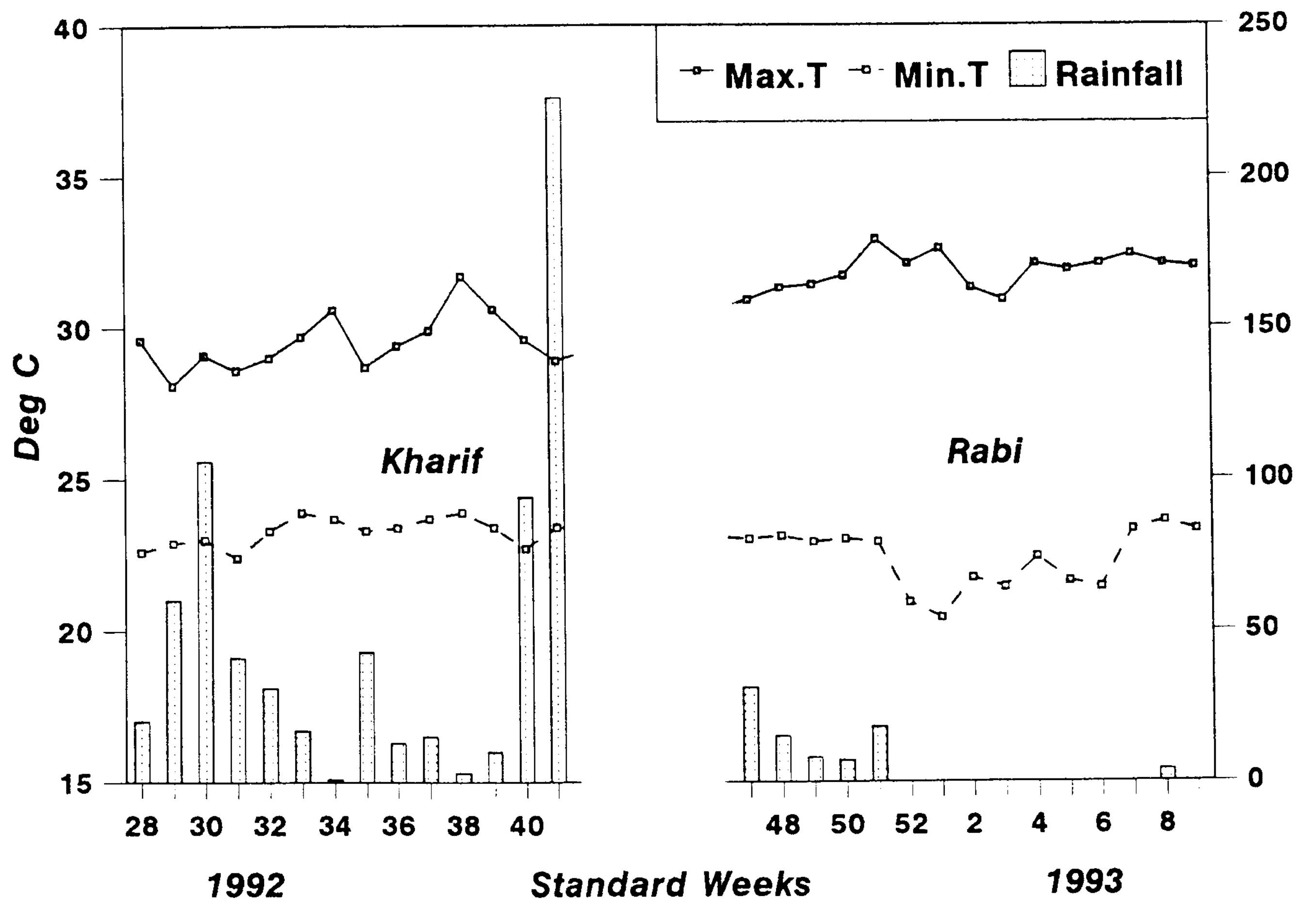
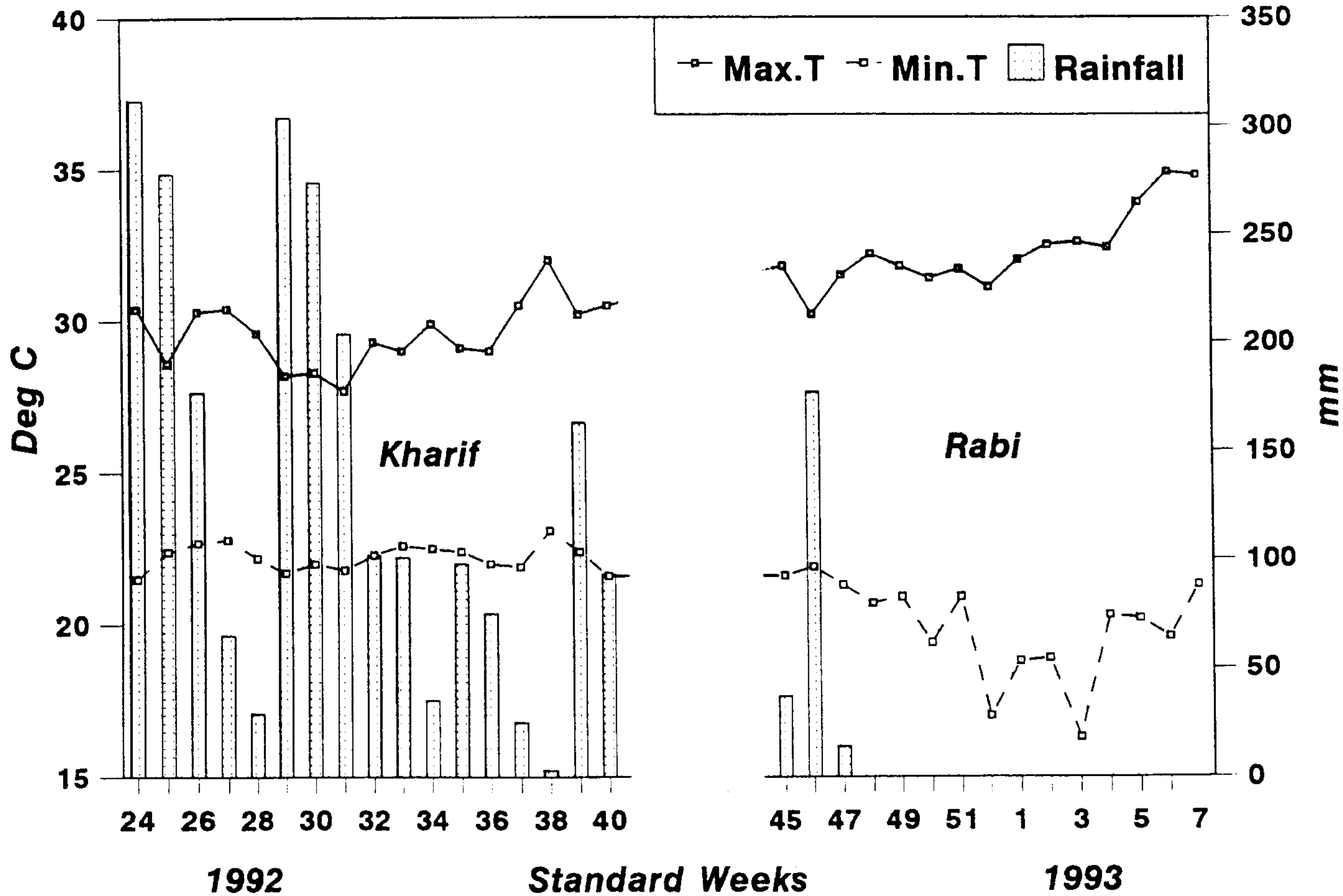


Fig.2(b) **WEATHER DURING THE EXPERIMENT PERIOD AT RARS, PATTAMBI (1992-93)**



3.3.2 Details of layout of experiment

Replication	:	3
Design	:	2x4+1 Randomised Complete Block Design
Gross plot size	:	24.75 m^2
Net plot size	:	20 m^2
Variety	:	*Jyothi*
Spacing	:	15 cm x 15 cm (*Kharif*)
		20 cm x 10 cm (*Rabi*)

3.3.3 Fertilizers

Nitrogen, phosphorus, potassium and sulphur were applied as urea, ammonium sulphate, ammonium phosphate sulphate, potassium dihydrogen orthophosphate and muriate of potash. N, P_2O_5 and K_2O were supplied to the experimental crop @ 90 : 53 : 45 kg ha^{-1} respectively.

3.3.4 Plant protection

No serious pests or diseases occured during the cropping periods. Pest surveillance was made and sulphur free pesticides were used for plant protection.

3.3.5 Observations recorded

3.3.5.1 Biometric observations such as, height of plants, number of tillers per hill and LAI were recorded as suggested by Matsushima (1980) and statistically analysed as suggested by (Gomez and Gomez, 1976) and presented.

3.3.5.2 Yield and yield attributes - yield of grain, yield of straw, number of productive tillers, number of grains per ear head, percentage of mature grains, weight of panicle, 1000 grain weight, grains : straw ratio, total drymatter production, harvest index and sink capacity were recorded, statistically analysed and presented (weights of grain and straw were given on dry weight basis). Sink capacity in rice is expressed on a unit of land area basis, as,

Sink capacity = Panicles per unit area x spikelets per panicle x individual gain weight

and expressed as g per m^2 (Venkateswarlu and Visperas, 1987).

3.3.5.3 Incidence of pests - score of intensity of gall fly, whorl maggot and green algae recorded were analysed after transformation ($\sqrt{x+1}$) and presented (Anon, 1980).

3.3.5.4 Chemical analysis of straw and grain for their S, N, P, K, Ca, Mg, Zn, Mn and Cu contents were conducted. The contents of these elements, protein in grain and straw and nutrient uptake were statistically analysed and presented (Jackson, 1958 and Yoshida *et al.*, 1976).

3.3.5.5 The agronomic efficiency, physiological efficiency and apparent recovery efficiency were worked out as per the procedure suggested by Craswell and Godwin (1984).

$$\text{Agronomic efficiency} = \frac{\text{Grain yield of fertilized crop (kg)} - \text{Grain yield of unfertilized crop (kg)}}{\text{Quantity of fertilizer applied (kg)}}$$

(expressed in kg kg^{-1})

Physiological efficiency =

$$\frac{\text{Total dry matter yield of fertilized crop (kg)} - \text{Total dry matter yield of unfertilized crop (kg)}}{\text{Nutrient uptake by fertilized crop (kg)} - \text{Nutrient uptake by unfertilized crop (kg)}}$$

(expressed as kg kg^{-1})

Apparent recovery efficiency =

$$\frac{\text{Nutrient uptake by fertilized crop} - \text{Nutrient uptake by unfertilized crop}}{\text{Quantity of fertilizer applied}} \times 100$$

(expressed as percentage)

3.3.5.6 Economics of S fertilization was worked out and presented. The value of input and out put used for the estimation of economics of sulphur application are detailed below:

Location and crop	Value Rs. kg^{-1}		Labour wages (men/women) Rs. day^{-1}	Total cost of cultivation Rs.
	Grain	Straw		
1. Alluvial soil (Karamana) *Kharif* season	4.00	0.50	68.00	11434.00
2. Alluvial soil (Karamana) *Rabi* season	4.20	0.60	70.00	11934.00
3. Brown hydromorphic soil (Pattambi) *Kharif* season	4.00	0.50	68.00	11134.00
4. Brown hydromorphic soil (Pattambi) *Rabi* season	4.20	0.60	70.00	11734.00

Ammonium sulphate Rs.4.56 kg^{-1}
Urea Rs.3.40 kg^{-1}
Ammonium phosphate sulphate Rs.6.20 kg^{-1}
Muriate of potash Rs.3.81 kg^{-1}
Mussoriephos Rs.1.77 kg^{-1}

[The cost of cultivation has been prepared taking in to account of wages in the locality, the different methods followed (like land preparation) and cost of the labour and inputs].

Total income per hectare, net income per hectare, benefit : cost ratio, physical optimum level of sulphur and the response surface of sulphur are estimated and presented.

3.3.5.7 Bulk crop - A blank crop without treatments was cultivated during *Rabi* season in the plots of *Kharif* crop to study the residual effect of sulphur. Fertilizers were applied @ 90 : 45 : 45 N, P_2O and K_2O respectively per ha. Plant protection with S free chemicals carried out. The data on grain and straw yield were recorded analysed and presented.

3.4 Part-IV. Sulphur use efficiency of rice

Utilization of applied sulphur by rice was evaluated in a pot culture experiment using ^{35}S labelled ammonium sulphate (AS) and ammonium phosphate sulphate (APS). These two fertilizer materials were selected as these were the source of S used in the field experiments. About 250 kg soil from each locations (viz. CSRC, Karamana and RARS, Pattambi) was collected in clean polythene gunnies, shade dried and sieved through 2 mm sieve. These soils were used for pot culture (in Plastic pots) with ^{35}S labelled (sp. activity 0.04517 mCi $g^{-1}S$) ammonium sulphate and ammonium phosphate sulphate.

3.4.1 Technical programme

(1) Treatments - 9

T_1 - Control (no sulphur)

T_2 - Ammonium sulphate (24% S) @ 10 kg labelled S ha^{-1}

T_3 - Ammonium sulphate (24% S) @ 20 kg labelled S ha^{-1}

T_4 - Ammonium sulphate (24% S) @ 30 kg labelled S ha^{-1}

T_5 - Ammonium sulphate (24% S) @ 40 kg labelled S ha^{-1}

T_6 - Ammonium phosphate sulphate (15% S) @ 10 kg labelled S ha^{-1}

T_7 - Ammonium phosphate sulphate (15% S) @ 20 kg labelled S ha^{-1}

T_8 - Ammonium phosphate sulphate (15% S) @ 30 kg labelled S ha^{-1}

T_9 - Ammonium phosphate sulphate (15% S) @ 40 kg labelled S ha^{-1}

Quantity of soil used per pot	: 5 kg
Variety of rice cultured	: *Jyothi*
Number of seedlings planted and maintained per pot	: 6 (Seedlings were prepared by Dapog nursery)

The crop was raised under flooded conditions.

3.4.2 Fertilizers used

AR grade urea, KH_2PO_4 and KCl were used in addition to tagged AS and APS to fertilize the plots with N,P_2O_5 and K_2O @ 90, 53 and 45 kg N, PO_5 and K_2O ha^{-1}.

3.4.3 Observations recorded

The plants were harvested by cutting at ground level and yield of grain (g pot^{-1}) and yield of straw (g pot^{-1}) were recorded. The samples were dried in oven at 70°C for 5 days till constant weights obtained.

3.4.4 Radioassay

Straw and grain samples @ 1 g each were digested using diacid (HNO_3 + $HClO_4$ @ 2:1). The digested samples were made up to 100 ml and stored in sample bottles and kept for settling of silica. One millilitre of the extract was mixed with 15 ml of a dioxane based scintillation mixture in a counting vial and counted in a Wallac 1409 Liquid Scintillation Counter.

Scintillation mixture used was Bray's scintillator (Yoshida *et al.*, 1976) containing POP-4 g, POPOP-0.2 g, Naphthalene-60 g, Methanol-100 ml and Ethylene glycol 20 ml for every thousand ml. The volume of the mixture was made to 1000 ml using Dioxane.

3.4.5 Chemical analysis

The S content in the acid digests of straw and (Section 3.4.4) grain were estimated by turbidimetry. From the above observations the specific activity of sulphur and the sulphur use efficiency of added sources were worked out statistically analysed and presented.

Computation formulae for sulphur use efficiency:

a) Specific activity in grain $= \dfrac{\text{dpm in grain}}{\mu\text{g S in grain}}$

b) Specific activity in straw $= \dfrac{\text{dpm in straw}}{\mu\text{g S in straw}}$

c) Specific activity in whole plant $= \dfrac{\text{dpm in grain + dpm in straw}}{\mu\text{g S in grain} + \mu\text{g S in straw}}$

d) Per cent S derived from fertilizer in plants (Sdff)

$$= \frac{\text{Specific activity of the plant (dpm } \mu\text{g}^{-1}\text{ S)}}{\text{Specific activity of the fertilizer (dpm } \mu\text{g}^{-1}\text{ S)}} \times 100$$

e) Per cent S derived from soil (Sdfs) = 100 - Sdff

f) A-value (ppm)

$$= \frac{\%\ \text{Sdfs}}{\%\ \text{Sdff}} \times \mu\text{g S applied g}^{-1}\text{ soil}$$

g) Quantity of S taken from fertilizer by plants(mg pot^{-1})

$$= \frac{\%\ \text{Sdff x Total S uptake}}{100}$$

h) Per cent utilization of applied S by plants (Sulphur use efficiency)

$$= \frac{\text{S in plant taken up from fertilizer (mg pot}^{-1}\text{)}}{\text{applied S mg pot}^{-1}} \times 100$$

3.4.5 Statistical analysis

The pot culture was done as completely Randomised Design with 9 treatments and 3 replications (Chang, 1972).

Results

4. RESULTS

4.1 Part-I. Assessment of the sulphur status of rice soils of Kerala

The data of chemical analysis of soils samples collected from alluvial and brown hydromorphic rice soils of 10 important rice growing districts of Kerala are tabulated and presented here. The analytical data obtained from four replicated analysis were tabulated in to ranges and means of different forms of sulphur and presented in Tables 1 and 3; and are the grouped in to categories of low, medium and high based on the SO_4-S content and presented in Tables 2, 4 and 5.

4.1.1 Sulphur status of alluvial soil

The ranges and mean values of different forms of sulphur in alluvial soil are presented district wise in Table 1. It can be seen that samples from alluvial soils of Kollam district has the lowest content of sulphur with 3.45 ppm SO_4-S and 81.75 ppm total sulphur. The mean sulphur content in samples from Alappuzha is the highest where the mean soluble SO_4-S is 47.23 ppm with a mean total S content of 722.71 ppm. The ranges of SO_4-S and total sulphur in alluvial soil are 0.9 to 236.1 ppm and 63.6 to 2204.5 ppm. Based on the mean values of SO_4-S in soil samples, Kollam has the lowest level of S availability. Alappuzha, Malappuram and Kottayam have above 15 ppm of available SO_4-S and are sulphur rich districts.

Table 2 shows that 56 per cent of the alluvial soil of Kerala are deficient in available sulphur content. Out of 29 soil samples from Palghat district, which is considered the rice bowl of Kerala, 15 had highly deficient sulphur status. On the

Table 1. Sulphur status of rice soils (Alluvial)
(Ranges and means) [ppm]

District		Soluble sulphate-S	Adsorbed sulphate-S	Organic + nonsulphate-S	Total S
1. Palakkad	Range	0.9-18.2	1.8-19.6	88.2-312.1	90.9-349.9
	Mean	7.69	5.46	165.41	178.56
2. Thrissur	Range	0.9-38.2	1.8-59.5	70.0-256.8	72.7-354.5
	Mean	8.21	11.08	147.11	166.40
3. Ernakulam	Range	4.6-13.2	1.8-16.8	111.8-183.6	118.2-213.6
	Mean	8.00	1.82	126.81	163.63
4. Malappuram	Range	2.3-86.5	1.8-149.6	95.8-436.6	99.9-672.7
	Mean	17.55	17.81	272.16	307.52
5. Alappuzha	Range	2.3-236.1	1.8-621.1	59.5-1347.3	63.6-2204.5
	Mean	47.23	100.96	574.52	722.71
6. Kottayam	Range	15.5-18.6	50.0-55.5	559.9-724.5	625.4-798.6
	Mean	17.20	53.26	649.04	719.50
7. Kollam	Range	2.3-4.6	1.8-2.2	59.5-93.1	63.6-99.9
	Mean	3.45	2.00	76.30	81.75
8. Thiruvanantha-puram	Range	2.3-15.5	2.2-7.3	81.9-213.9	86.4-236.7
	Mean	8.94	4.54	121.40	134.62
9. Kannur	Range	3.6-13.2	4.6-26.3	160.0-241.3	168.2-280.8
	Mean	7.50	11.70	183.95	203.15
Total	Range	0.9-236.1	1.8-621.1	59.5-1347.3	63.6-2204.5
	Mean	16.89	27.33	263.34	302.89

Table 2. Available S content of rice soils of Kerala (Alluvial)

Name of district	No.of soil samples	Number of soil samples belongs to				Percentage of S deficient samples
		Low		Medium	High	
		Highly deficient (<5 ppm)	Deficient (5-10 ppm)	Satisfactory (10-15 ppm)	Good (>15 ppm)	
1. Palakkad	29	15	4	7	3	66
2. Thrissur	21	8	9	2	2	81
3. Ernakulam	4	2	1	1	-	75
4. Alappuzha	19	2	1	2	14	16
5. Malappuram	18	6	3	1	8	50
6. Kottayam	3	-	-	-	3	0
7. Kollam	2	2	-	-	-	100
8. Thiruvanantha-puram	5	1	2	1	1	60
9. Kannur	4	2	1	1	-	75
Total	105	38	21	15	31	56

whole excepting Alappuzha and Kottayam districts, where the alluvial soils predominantly belong to Karapadam, all other districts have above 50 per cent of rice fields with sulphur deficiency. Out of 105 samples 38 samples (36%) have only less than 5 ppm SO_4-S and are highly deficient in sulphur status.

4.1.2 Sulphur status of brown hydromorphic soils

Table 3 which shows the ranges and mean of SO_4-S, adsorbed SO_4, organic sulphur and total sulphur indicate that except Malappuram in all other districts the mean SO_4-S contents are less than 10 ppm. The mean value of SO_4-S in Malappuram is more than double of the other areas which shows that this area has more sulphur rich soil. This is the pattern seen in the case of adsorbed sulphur, organic sulphur and total sulphur; which are considerably high in Malappuram compared to other districts. The grand mean values of sulphur status shows that brown hydromorphic soils in general are poor in soluble SO_4-S, adsorbed S, organic-S and total S. The mean soluble SO_4-S in these soils are less than half of that in alluvial soil.

Table 4 shows that the brown hydromorphic soils are more deficient than alluvial soils. Here, 83 per cent soils are in the deficient category and 52 per cent soils fall in the highly deficient level of less than 5 ppm SO_4-S. All the districts have more than 65 per cent soils with sulphur deficiency. Of Kannur and Kozhikkode districts all the samples contained less than 5 ppm SO_4-S. The Palghat and Thrissur districts which contributes more than 30 per cent of hydromorphic soils have more than 80 per cent soils deficient in SO_4-S.

Table 3. Sulphur status of rice soils (Brown hydromorphic)
(Ranges and means) [ppm]

District		Soluble sulphate-S	Adsorbed sulphate-S	Organic + nonsulphate-S	Total S
1. Palakkad	Range	0.9-22.3	1.8-11.8	65.5-225.0	68.2-259.1
	Mean	6.65	6.80	168.93	182.38
2. Thrissur	Range	0.9-12.3	1.8-13.2	83.7-283.6	86.4-309.1
	Mean	5.65	5.80	176.99	188.44
3. Ernakulam	Range	0.9-10.0	0.9-13.6	111.8-258.2	113.6-281.8
	Mean	3.85	5.59	194.61	204.05
4. Malappuram	Range	4.6-67.8	3.2-91.9	155.8-790.20	163.6-949.9
	Mean	22.97	20.00	350.53	393.50
5. Alappuzha	Range	2.3-14.1	1.8-19.10	132.3-289.50	136.4-322.7
	Mean	7.90	10.92	213.76	232.58
6. Kottayam	Range	0.9-14.6	0.9-10.9	93.6-288.1	95.4-313.6
	Mean	3.55	2.90	149.92	156.37
7. Kollam	Range	2.3-13.2	1.3-14.6	132.8-290.4	136.4-318.2
	Mean	8.44	6.86	199.05	214.35
8. Thiruvananthapuram	Range	4.6-15.5	4.1-10.4	195.8-246.8	204.5-272.7
	Mean	8.6	8.15	217.31	234.06
9. Kannur	Range	2.7-4.5	2.7-5.0	171.9-231.4	177.3-240.9
	Mean	3.74	4.04	199.96	207.74
10. Kozhikkode	Range	2.7-4.9	1.9-3.2	181.8-205.5	186.4-213.6
	Mean	3.73	2.46	192.27	198.46
Total	Range	0.9-67.8	0.9-91.9	65.5-79.02	68.2-949.9
	Mean	7.02	7.07	196.09	210.96

Table 4. Available S content of rice soils of Kerala (Brown hydromorphic)

Name of District	No. of soil samples	No. of soil samples belongs to				Percentage of S deficient samples
		Low		Medium	High	
		Highly deficient (<5 ppm)	Deficient 5-10 ppm	Satisfactory 10-15 ppm	Good (>15 ppm)	
1. Palakkad	25	12	8	2	3	80
2. Thrissur	11	5	5	1	-	91
3. Ernakulam	19	13	5	1	-	95
4. Alappuzha	6	2	2	2	-	66
5. Malappuram	7	1	4	-	2	71
6. Kottayam	8	7	-	1	-	88
7. Kollam	13	4	6	3	-	77
8. Thiruvananthapuram	6	1	3	1	1	66
9. Kannur	7	7	-	-	-	100
10. Kozhikkode	3	3	-	-	-	100
Total	105	55	38	11	6	83

4.1.3 Sulphur status of major rice soils in Kerala

The analytical data of SO_4-S in alluvial and brown hydromorphic soils are combined and classified in to different categories of S-status and presented in Table 5. Here number of samples that fell in different category and their percentages are given. Out of 210 samples studied from various locations, 92 samples fall in highly deficient category with less than 5 ppm S. The overall grouping shows that 70 per cent soils fall in deficient level of S, 12 per cent in satisfactory level (between 10 to 15 ppm) and 18 per cent in good level.

The district wise information shows that more than 50 per cent of the soils in all districts except Alappuzha fall in deficient level. In Alappuzha 56 per cent of the soils are having good level of sulphur and the deficiency is only in 28 per cent of the soils sampled. The percentage of deficiency in the major rice districts having brown hydromorphic soils, viz. Palakkad, Thrissur and Ernakulam are 72, 84 and 91, respectively.

4.1.4 Relationship of sulphur forms with organic carbon content and pH

The different forms of sulphur in alluvial and brown hydromorphic soils were studied for their relationship with organic carbon content and pH of the soils. The correlation coefficients are presented in Tables 6 and 7.

It is seen from the tables that the soluble SO_4-S has significant positive correlation with adsorbed SO_4-S and total S in both types of rice soils. The organic carbon content in both soils are having significantly high and positive correlation

Table 5. Available S status of major rice soils of Kerala

Name of District	No. of soil samples analysed (Total)	Low			Medium		High	
		Highly deficient samples < 5 ppm	Deficient samples 5-10 ppm	Total % of deficient soil sample	Satisfactory samples 10-15 ppm	Total % of satisfactory level samples	Good samples >15 ppm	Total % of good level samples
1. Palakkad	54	27	12	72	9	16	6	11
2. Thrissur	32	13	14	84	3	9	2	6
3. Ernakulam	23	15	6	91	2	9	-	-
4. Alappuzha	25	4	3	28	4	16	14	56
5. Malappuram	25	7	7	56	1	4	10	40
6. Kottayam	11	7	-	64	1	9	3	27
7. Kollam	15	6	6	80	3	20	-	-
8. Thiruvananthapuram	11	2	5	64	2	18	2	18
9. Kannur	11	8	2	91	1	9	-	-
10. Kozhikkode	3	3	-	100	-	-	-	-
Total	210	92	55	70	26	12	37	18

Table 6. Coefficients of correlation between forms of sulphur and soil properties (Alluvial soil)

Soil properties	Forms of sulphur			
	O.C.	Total S	Available S	
			Soluble SO_4-S	Adsorbed SO_4-S
pH	-0.6169**	-0.5898**	-0.4063**	-0.3672**
Organic carbon		0.8965**	0.5857**	0.9267**
Total sulphur			0.8243**	0.8180**
Soluble SO_4-S				0.9267**

**Significant at 1% level

Table 7. Coefficients of correlation between forms of sulphur and soil properties (Brown hydromorphic soil)

Soil properties	Forms of sulphur			
	O.C.	Total S	Available S	
			Soluble SO_4-S	Adsorbed SO_4-S
pH	-0.3987**	-0.4425**	-0.3716**	-0.2205*
Organic carbon		0.8957**	0.7927**	0.6180**
Total sulphur			0.8911**	0.7410**
Soluble SO_4-S				0.7287**

* Significant at 5% level
**Significant at 1% level

with different forms of sulphur. However, the pH of the soil have negative correlation with organic carbon as well as forms of sulphur in both the soil types. The correlation of pH is significantly negative at 1 per cent level, with adsorbed SO_4-S in alluvial soil. But the negative correlation was significant at 5 per cent level only in brown hydromorphic soil.

4.2 Part-II. Identification of suitable soil test procedure for estimation of available sulphur

Based on the delineation of soils in to low, medium and high in Part I, 30 soils from each type viz. alluvial and brown hydromorphic were selected with representations in low, medium and high categories, and used in this part of study. These soils were analysed for their sulphur content with 12 extractants, replicated 4 times, after standardisation (Freney, 1958) and analytical results are presented along with results of pot culture.

4.2.1 Estimation of S by different methods - Alluvial soil

The quantity of S_4-S estimated in 30 soils of alluvial type with 12 extractants are presented in Table 8. The mean values of SO_4-S estimated by different extractants shows that out of the 30 locations 10 belonged to low (< 10 ppm), 9 locations belonged to medium (between 10 and 15 ppm) and 11 belonged to high (> 15 ppm). The highest mean value was in location A.5, which was found to contain high level of available sulphur under all the methods of estimation. The lowest mean value of SO_4-S (3.2 ppm) was seen in location A.16 (Mannar). This soil fell in low level category of SO_4-S under all the methods of estimation.

Table 8. Sulphur extracted (ppm) by extractants (Alluvial soil)

Location No.	Water A	NaCl B	NH_4OAc C	$CaCl_2$ D	NH_4F+ HCl E	NH_4OAc+ HOAc F	$Ca(H_2PO_4)_2$) G
A.1	4.2	6.6	8.2	4.4	10.8	16.2	13.3
A.2	5.2	3.3	7.4	2.5	10.7	14.4	14.2
A.3	5.6	4.7	10.2	3.3	12.3	18.3	9.3
A.4	6.4	5.4	10.4	9.2	9.3	17.7	15.4
A.5	19.2	23.3	25.3	12.7	28.2	29.2	33.5
A.6	18.1	27.7	20.1	18.9	25.3	23.1	32.7
A.7	19.3	24.4	21.1	10.5	19.2	25.3	28.2
A.8	3.6	5.5	10.2	2.3	4.6	12.2	5.2
A.9	2.7	3.7	7.3	0.7	2.7	2.4	2.3
A.10	8.2	11.2	13.0	12.2	12.2	9.1	19.1
A.11	9.1	10.4	14.2	13.3	14.2	11.3	20.2
A.12	5.2	12.2	24.2	14.2	26.0	24.7	28.1
A.13	10.1	6.9	8.2	8.9	12.4	13.2	16.2
A.14	6.4	12.3	17.2	10.2	23.4	16.1	15.2
A.15	9.1	7.9	10.3	8.4	12.7	13.2	15.3
A.16	2.3	3.2	3.2	0.9	2.7	5.3	2.7
A.17	4.2	5.1	12.1	4.4	10.2	14.1	5.3
A.18	5.1	10.3	17.4	8.3	17.4	18.2	13.2
A.19	8.4	9.4	14.4	9.1	15.5	21.0	16.4
A.20	6.2	7.7	13.0	3.5	9.2	13.2	5.7
A.21	9.1	13.5	20.3	12.3	16.2	23.0	18.3
A.22	8.2	10.3	23.6	10.2	19.1	25.1	18.2
A.23	10.7	11.3	16.7	12.4	18.2	13.2	14.4
A.24	9.8	7.4	11.2	3.2	12.3	8.3	5.5
A.25	6.6	7.2	8.4	3.4	9.2	9.2	6.6
A.26	5.6	8.9	9.5	3.2	11.2	12.2	7.7
A.27	9.4	9.9	19.4	12.3	16.2	16.7	24.2
A.28	1.7	4.2	4.2	2.1	3.3	5.6	4.2
A.29	9.3	9.2	14.3	9.3	12.2	9.2	19.7
A.30	6.2	5.6	8.3	2.9	8.4	7.1	5.2

Contd.

Table 8. Continued

Location No.	KH_2PO_4 H	$Ca(H_2PO_4)_2$ + HOAc I	NaOAc+ HOAc J	$NaHCO_3$ K	NH_4Cl L	Mean
A.1	14.2	13.2	12.1	16.9	6.5	10.5
A.2	15.2	13.4	10.2	17.2	3.2	9.7
A.3	12.1	15.2	13.2	19.3	4.7	10.7
A.4	18.3	14.2	12.2	13.7	12.5	12.1
A.5	39.2	37.5	26.1	36.2	17.2	27.3
A.6	32.0	29.4	22.4	28.4	22.2	24.5
A.7	23.0	26.3	27.2	26.3	16.1	22.2
A.8	6.2	3.7	8.7	20.2	6.5	7.4
A.9	5.3	2.2	4.7	12.4	1.6	4.0
A.10	19.3	17.2	14.5	24.7	14.7	14.6
A.11	18.1	18.1	16.2	34.9	16.6	16.4
A.12	22.4	23.2	21.3	36.7	15.7	21.2
A.13	16.6	12.1	8.4	20.3	9.4	11.9
A.14	19.2	15.4	11.4	32.4	14.5	16.1
A.15	19.3	14.2	8.2	19.7	14.3	11.9
A.16	3.3	2.2	2.7	7.4	2.7	3.2
A.17	8.2	12.4	4.1	18.8	3.2	8.5
A.18	19.1	16.4	13.2	29.2	8.2	14.7
A.19	20.2	14.3	3.5	28.3	9.3	14.1
A.20	8.2	4.5	7.2	18.7	2.5	8.3
A.21	22.1	18.6	14.6	30.1	10.4	17.4
A.22	24.0	18.7	17.7	34.6	10.6	15.3
A.23	21.1	16.6	15.3	31.7	5.5	15.6
A.24	10.2	11.4	10.2	18.3	2.9	9.2
A.25	9.2	9.5	9.7	20.2	5.5	8.7
A.26	9.4	10.3	10.5	21.2	4.6	9.5
A.27	24.7	22.2	14.3	29.1	12.7	17.8
A.28	4.7	3.6	3.9	9.5	2.9	4.2
A.29	22.2	16.1	13.2	24.4	9.0	13.9
A.30	10.3	6.4	7.3	19.7	2.3	7.5

The coefficient of correlation between different methods of S-estimation is presented in Table 9. It is seen that all the methods are significantly correlated between themselves. Among the extractants monocalcium phosphate has the highest level of correlation with all the extractants. Water has the highest significant correlation with potassium dihydrogen orthophosphate followed by monocalcium phosphate. Sodium chloride has the highest correlation to NH_4OAc + HOAc; followed by to $Ca(H_2PO_4)_2$. Ammonium acetate has the highest correlation to Olsen's reagent in S extraction. Calcium chloride has the highest correlation to ammonium chloride, $Ca(H_2PO_4)_2$ and $Ca(H_2PO_4)_2$ + HOAc. Bray's extractant correlated well to Olsen's reagent followed by monocalcium phosphate. NH_4OAc + HOAc has the highest correlation with ammonium acetate. Monocalcium phosphates has the higher correlation with NH_4Cl, $CaCl_2$, KH_2PO_4 and $Ca(H_2PO_4)_2$ + HOAc. Potassium dihydrogen orthophosphate has the highest correlation with monocalcium phosphate. The highest correlation of $(CaH_2PO_4)_2$ + HOAc is found to be with $Ca(H_2PO_4)_2$. Morgan's reagent has the highest correlation with NaCl and $Ca(H_2PO_4)_2$. Olsen's reagent has highest correlation with ammonium acetate followed by Bray's reagent, potassium dihydrogen orthophosphate and monocalcium phosphate. Ammonium chloride has the highest correlation with monocalcium phosphate followed by calcium chloride.

4.2.2 Identification of suitable S estimation procedure - Alluvial soil

The relative yield of grain, relative yield of straw, relative yield of total biomass and relative uptake of S by rice grown in alluvial soils are presented in

Table 9. Coefficients of correlation between different methods (Alluvial soil)

Sl. No.	Methods	B	C	D	E	F	G	H	I	J	K	L
A	Water	0.7279**	0.4168*	0.4784**	0.4600*	0.3710*	0.5830**	0.7566**	0.4240*	0.4243*	0.4747**	0.5825**
B	NaCl		0.7412**	0.7427**	0.8158**	0.7045**	0.8358**	0.7754**	0.7094**	0.8555**	0.7154**	0.7692**
C	NH_4OAc			0.7867**	0.8248**	0.7131**	0.7725**	0.7203**	0.7343**	0.7639**	0.9092**	0.7051**
D	$CaCl_2$				0.7882**	0.5996**	0.8646**	0.7789**	0.8360**	0.7727**	0.7435**	0.8776**
E	NH_4F+ HCl					0.8407**	0.8455**	0.7990**	0.8036**	0.7922**	0.8733**	0.7535**
F	NH_4OAc + HOAc						0.7725**	0.7081**	0.7495**	0.7126**	0.6932**	0.6247**
G	$Ca(H_2PO_4)_2$							0.8812**	0.8640**	0.8495**	0.7493**	0.8937**
H	KH_2PO_4								0.7060**	0.7711**	0.7858**	0.8115**
I	$Ca(H_2PO_4)_2$ + HOAc									0.7824**	0.6909**	0.7934**
J	NaOAc + HOAc										0.7236**	0.7346**
K	$NaHCO_3$											0.6749**
L	NH_4Cl											-

* Significant at 5% level
**Significant at 1% level

Table 10. The relative grain yield ranged between 72 to 102 per cent. The relative straw yield ranged between 71 to 102 per cent. The relative uptake of sulphur ranged from 31 to 95 per cent. The relative biomass yield ranged from 76 to 102 per cent.

The relative yields and the available sulphur in alluvial soil under different methods of sulphur extraction are plotted in scatter diagrams (Figs.3 to 14). The critical levels were estimated by Cate and Nelson procedure as is seen in the figures. Plates 1, 3 and 4 shows that the rice plants in sulphur applied pots performed better in both soils with more tillers, increase in height and with a vigorous growth.

Correlations between S extracted by various methods and yield parameters are presented in Table 10. With regard to relative grain yield the 'r' values are high for ammonium acetate + acetic acid followed by Olsen's reagent and three phosphate extractants used. The relative straw yield significantly correlated with S extraction methods of Olsen's reagent, followed by calcium chloride, ammonium chloride and monocalcium phosphate. In the case of relative uptake, the correlations were highest for ammonium acetate followed by calcium chloride, Olsen's reagent and monocalcium phosphate. Relative biomass production correlated well with Olsen's reagent followed by ammonium acetate + acetic acid, ammonium acetate, potassium dihydrogen orthophosphate and monocalcium phosphate.

The range of available sulphur under different procedures of extraction, the mean and median values, and the critical concentration of SO_4-S (in ppm) obtained from the scatter diagram are tabulated in Table 12.

The mean value of range from all extractants is 2.7 to 27.5 and mean critical concentration in alluvial soil is 12.2 ppm. The widest and closest ranges of

Table 10. Relative yield parameters (Alluvial soil)

Sample No.	Relative grain yield (%)	Relative straw yield (%)	Relative uptake of S (%)	Relative biomass yield (%)
1	84	81	41	82
2	84	84	43	84
3	89	89	54	89
4	87	92	46	89
5	102	102	83	102
6	96	93	79	94
7	98	96	61	95
8	84	82	34	83
9	79	83	54	81
10	92	97	74	94
11	93	97	90	95
12	100	99	95	99
13	89	94	50	91
14	95	95	75	95
15	95	97	74	96
16	72	83	49	77
17	87	86	52	85
18	96	97	67	96
19	93	96	71	94
20	85	82	72	93
21	94	95	73	94
22	98	98	78	98
23	96	96	63	96
24	88	87	43	87
25	86	87	40	86
26	87	90	60	88
27	95	96	85	95
28	75	82	54	78
29	91	95	87	93
30	82	71	31	76

Table 11. Coefficients of correlation between soil test values (ppm S) obtained by different methods and yield parameters (Alluvial soil)

Sl. No.	Methods	Relative grain yield	Relative straw yield	Relative uptake of sulphur	Relative total biomass production	Grain yield	S-content in grain	Straw yield	S-content in straw
A	Water	0.5248**	0.3704*	0.1827	0.4533**	0.4443*	0.2951	0.2667	0.4710**
B	NaCl	0.7538**	0.6238**	0.5466**	0.7033**	0.4418*	0.6380**	0.3605	0.7974**
C	NH_4OAc	0.8559**	0.7422**	0.7987**	0.8350**	0.5335**	0.6681**	0.5310**	0.6275**
D	$CaCl_2$	0.7848**	0.7585**	0.7289**	0.7636**	0.5357**	0.6467**	0.5353**	0.6770**
E	NH_4F+ HCl	0.7852**	0.6471**	0.5150**	0.7371*	0.4660*	0.4429*	0.4301*	0.5940**
F	NH_4OAc + HOAc	0.9010**	0.7410**	0.6687**	0.8354**	0.5018**	0.5934**	0.4799**	0.6351**
G	$Ca(H_2PO_4)_2$	0.8133**	0.7436**	0.6901**	0.7678**	0.6074**	0.6226**	0.5436**	0.6849**
H	KH_2PO_4	0.8218**	0.7042**	0.5655**	0.7682**	0.6120**	0.5362**	0.5240**	0.5614**
I	$Ca(H_2PO_4)_2$+ HOAc	0.8235**	0.7114**	0.6108**	0.7102**	0.5592**	0.5605**	0.4627*	0.6180**
J	NaOAc + HOAc	0.7729**	0.6131**	0.5031**	0.6913**	0.6464**	0.5806**	0.5412**	0.6317**
K	$NaHCO_3$	0.9070**	0.7507**	0.7227**	0.8567**	0.5318**	0.5601**	0.4854**	0,4992**
L	NH_4Cl	0.7572**	0.7489**	0.6744**	0.7308**	0.5755**	0.6327**	0.5252**	0.6661**

* Significant at 5% level
**Significant at 1% level

sulphur extracted are by potassium dihydrogen orthophosphate and water respectively. The critical concentration of available sulphur extracted by calcium chloride is the lowest (5 ppm). The Olsen's reagent ($NaHCO_3$) showed a high levels of critical concentration (22 ppm) below which sulphur is a limiting factor. The critical concentration of phosphate extractants and ammonium acetate + acetic acid remained the same value as 15 ppm. Along with calcium chloride, water, sodium chloride and ammonium chloride showed less than 10 ppm as critical levels as is seen in the figures and Table 12. The median values compared well with the mean values and critical concentrations.

Table 13 shows the responsiveness and the non responsiveness of addition of S @ 40 kg S ha^{-1} in the pot culture. The number of responsive soil out of 30 locations which had less than 7 ppm S when water was the extractant shows that there is increase in yield by S application to the tune of 21.2 per cent over control pots. The non-responsive soils (the S content estimated is above 7 ppm) also gave increased grain yield but was to the tune of 5.7 per cent. The table shows that monocalcium phosphate divides the soils in to exactly two groups of responsive and non responsive soils to which 15 out of 30 soils fall in. Here the increase in yield by responsive soils is to the tune of 17.5 per cent. The non-responsive soils shows a decrease of 0.1 per cent yield by application of sulphur. This shows that among the extractants used monocalcium phosphate is the best extractant as it identified non responsive soils more sharply and the procedure in which S is estimated using this extractant is the best method for estimating sulphur status in alluvial soils.

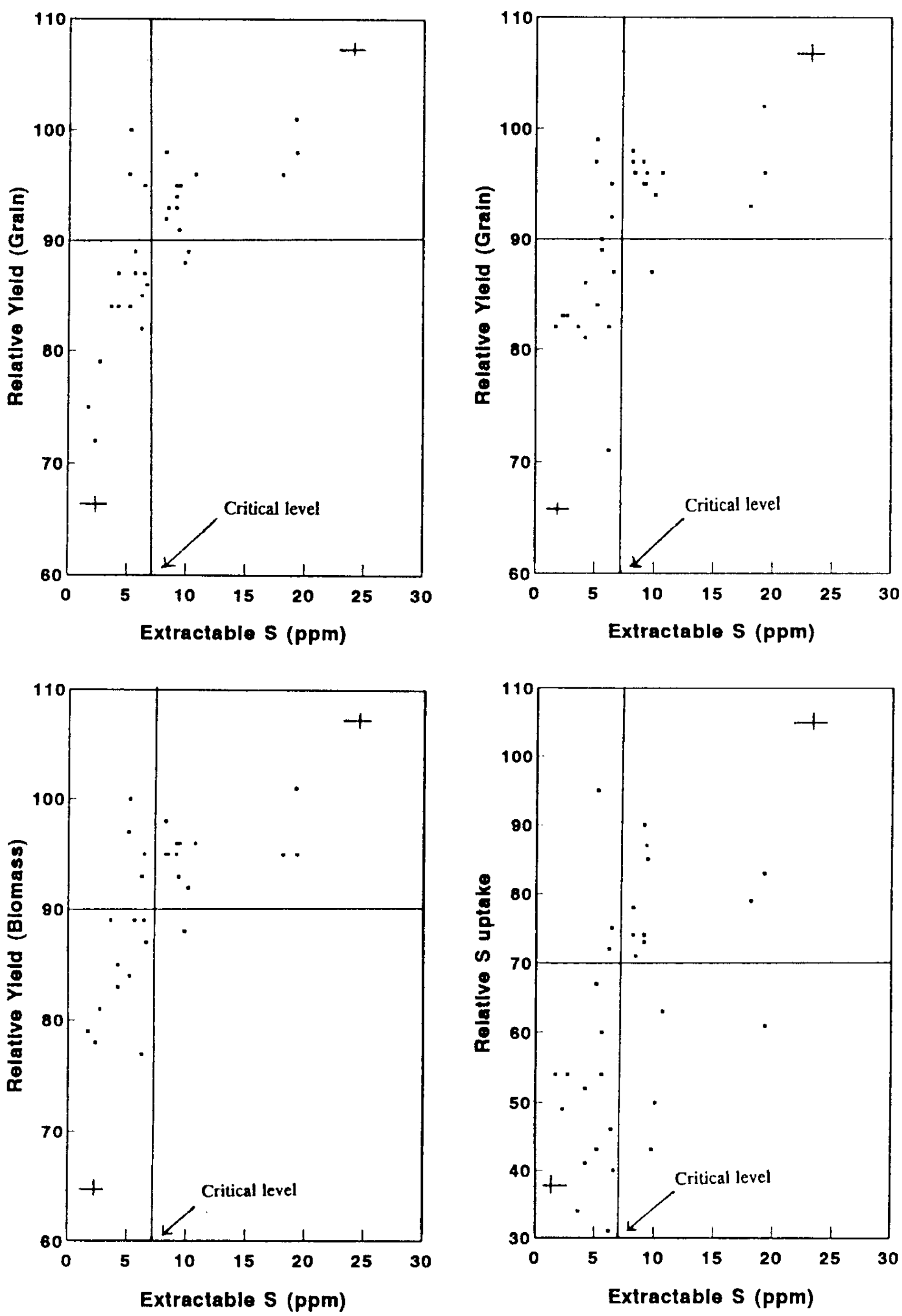


Fig. 3. **Relationship between extractable sulphur (ppm) and relative yields (Extractant - Water, soil-Alluvial)**

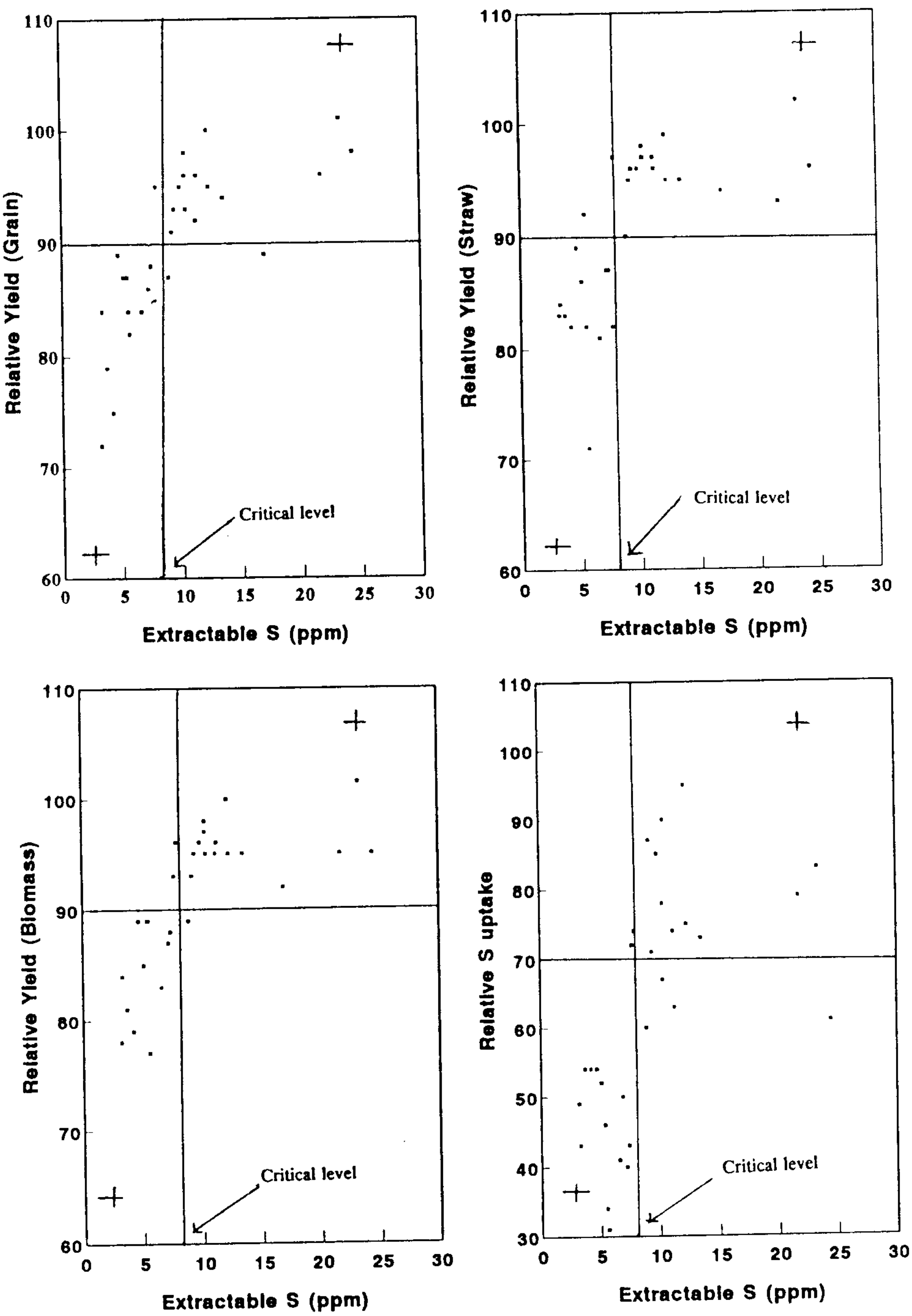


Fig. 4. Relationship between extractable sulphur (ppm) and Relative yields (Extractant - Sodium chloride,soil-alluvial)

A

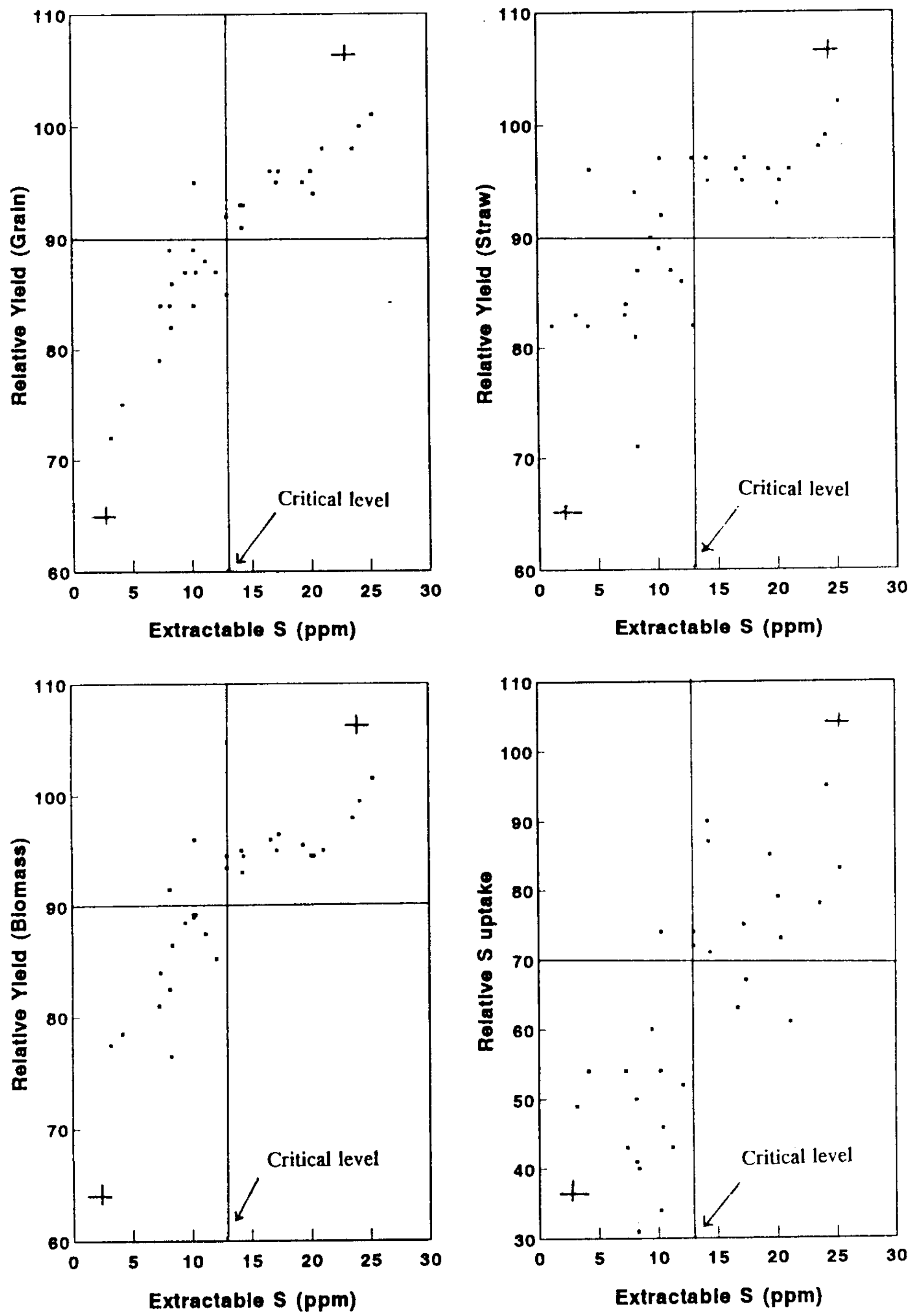


Fig. 5. Relationship between extractable sulphur (ppm) and Relative yields (Extractant - Ammonium Acetate, Soil-Alluvial)

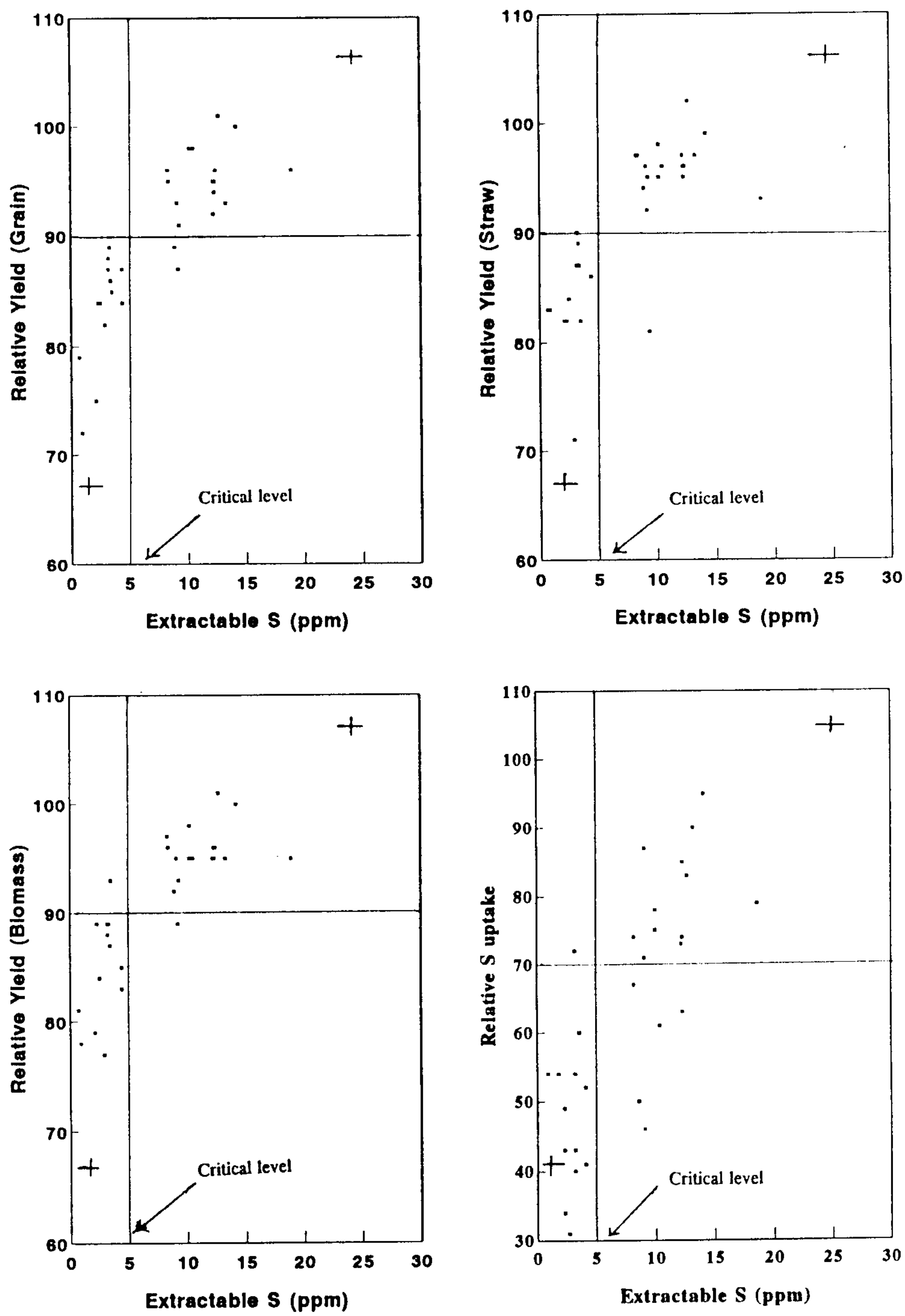


Fig. 6. **Relationship between extractable sulphur (ppm) and relative yields (Extractant - Calcium chloride, soil-Alluvial)**

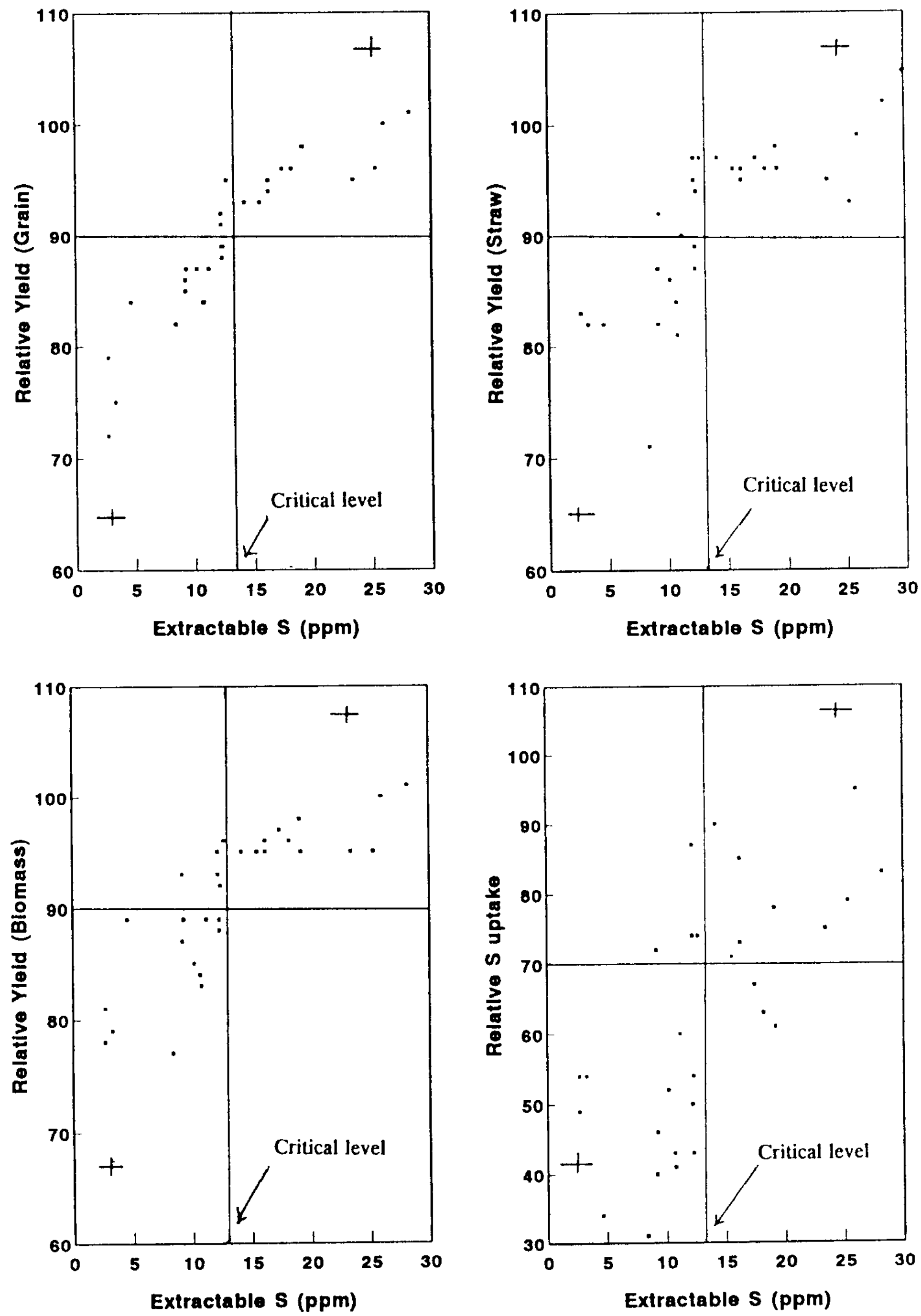


Fig. 7. **Relationship between extractable sulphur (ppm) and relative yields (Extractant - Bray's No.1, soil-Alluvial)**

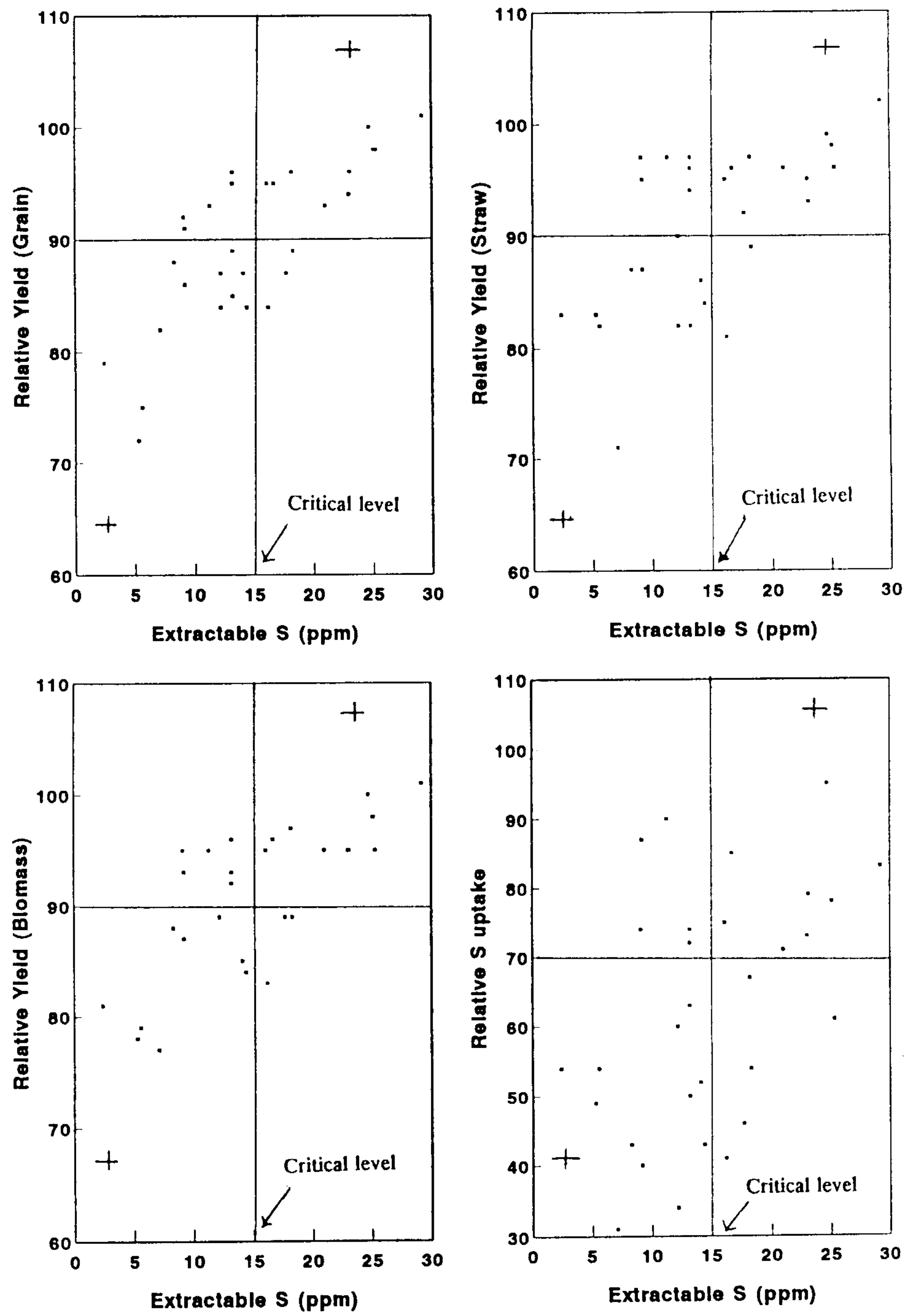


Fig. 8. **Relationship between extractable sulphur (ppm) and relative yields (Extractant - Ammonium Acetate + Acetic Acid, soil-Alluvial)**

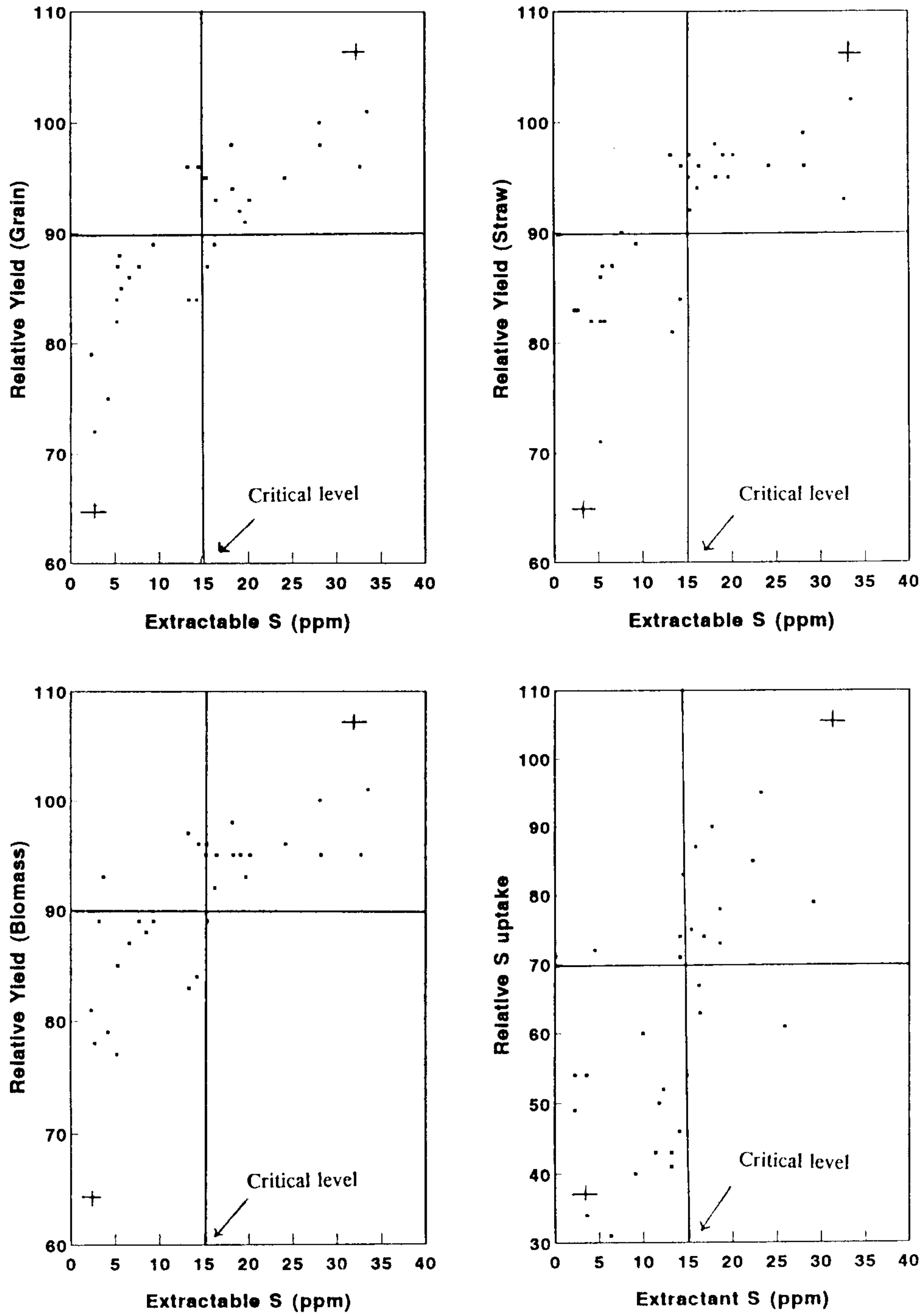


Fig. 9. **Relationship between extractable sulphur (ppm) and relative yields (Extractant - Monocalcium phosphate, soil-Alluvial)**

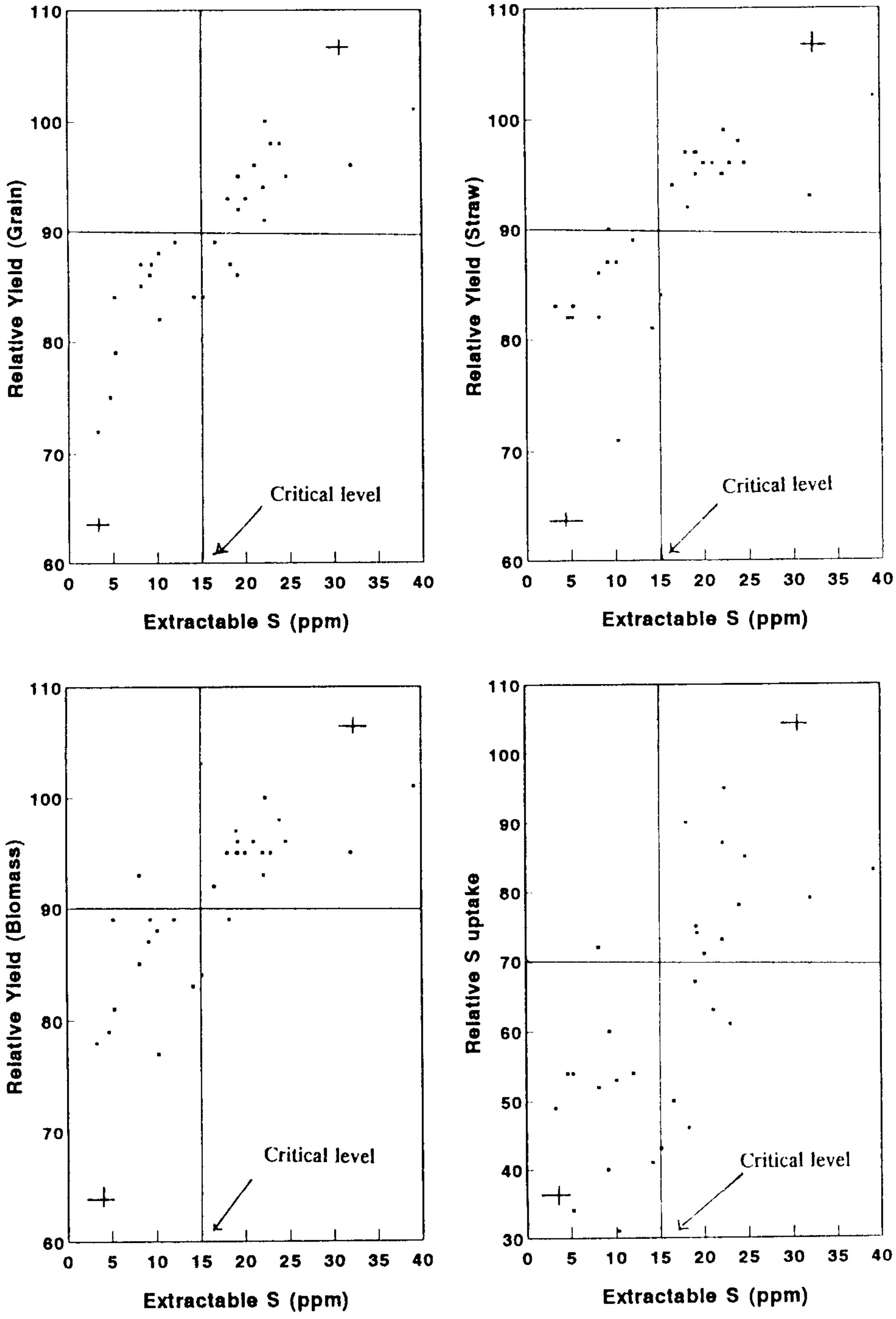


Fig. 10. **Relationship between extractable sulphur (ppm) and relative yields (Extractant - Potassium dihydrogen orthophosphate, soil-Alluvial)**

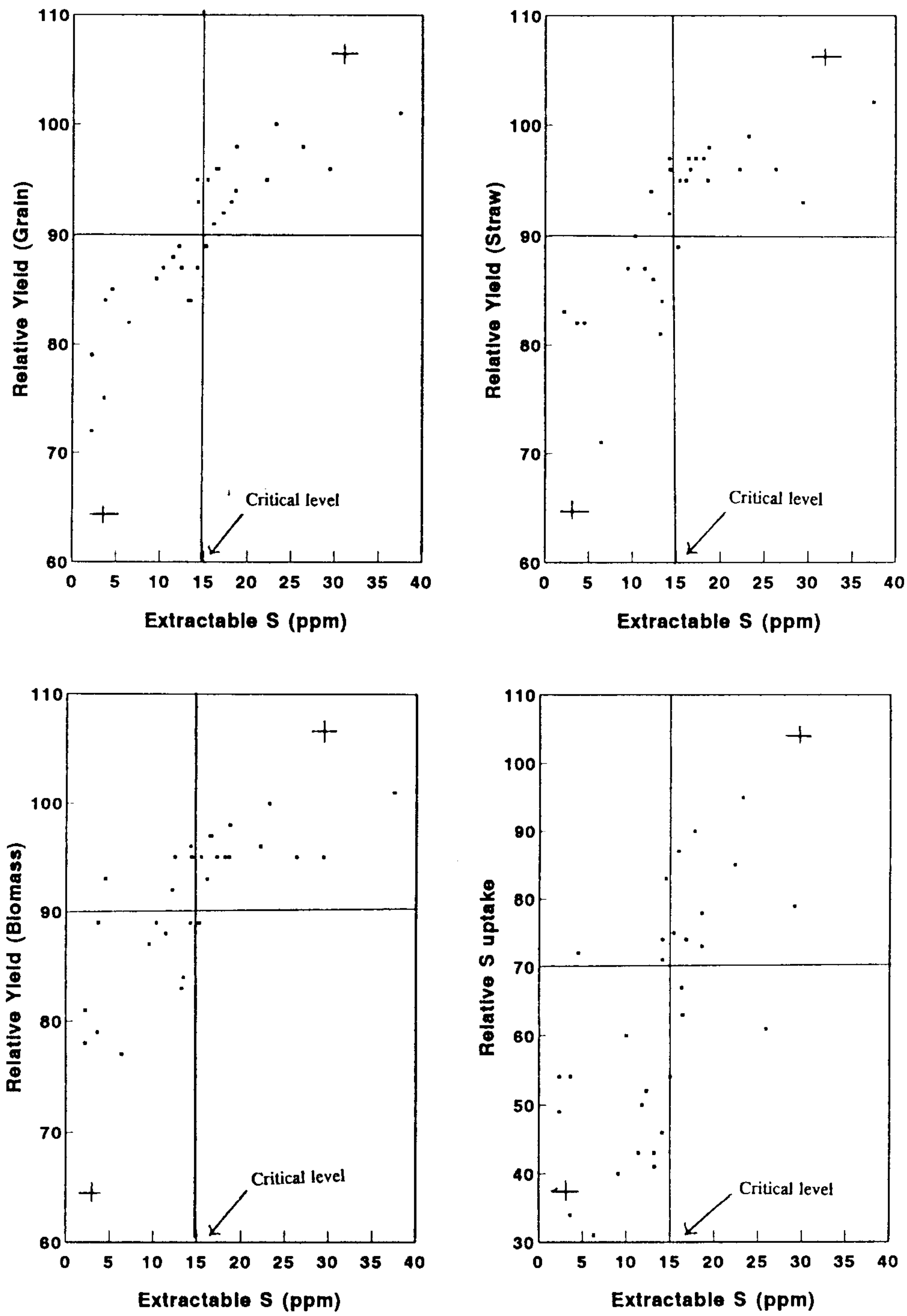


Fig. 11. **Relationship between extractable sulphur (ppm) and relative yields (Extractant - Monocalcium phosphate + Acetic Acid, soil-Alluvial)**

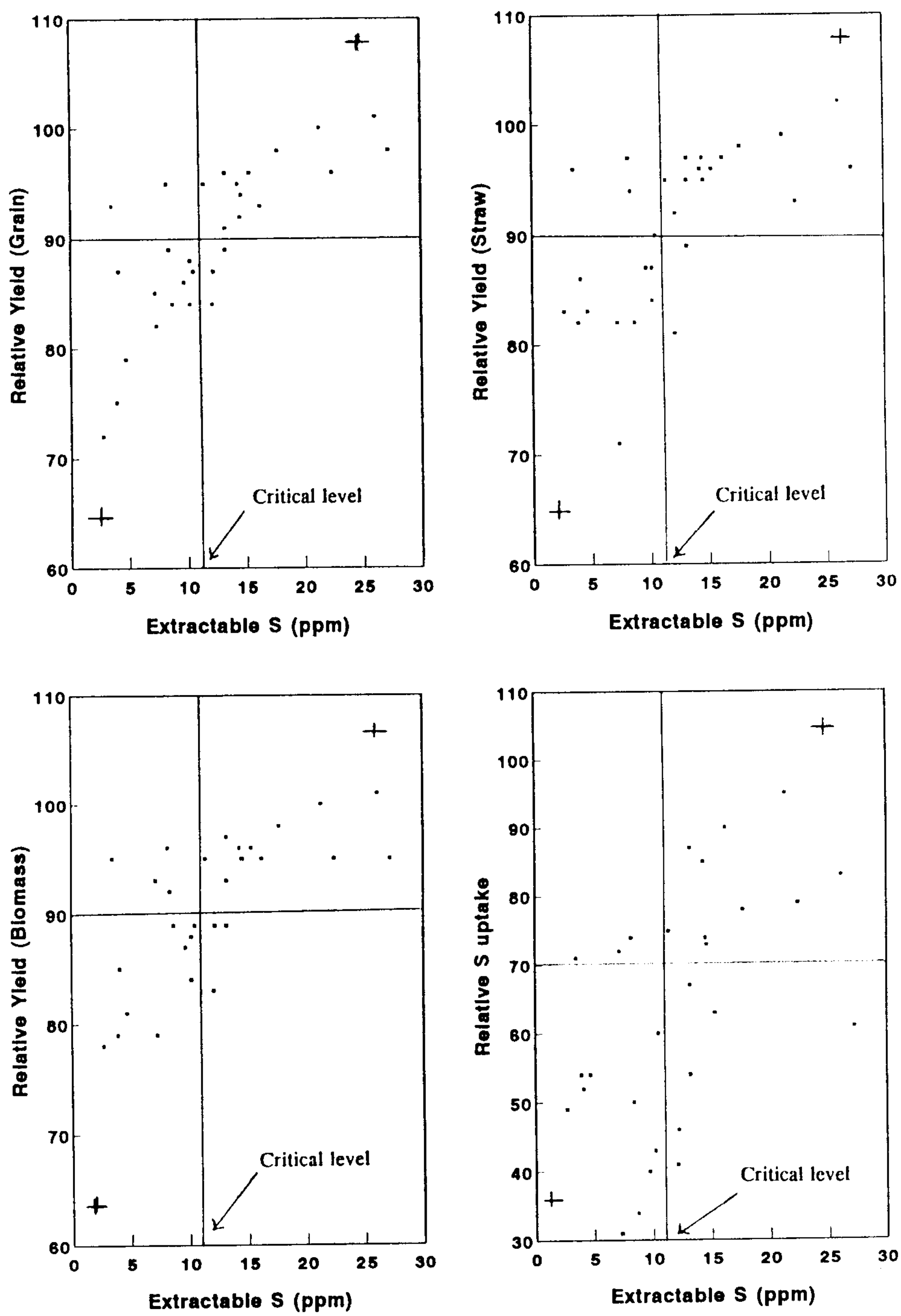


Fig. 12. **Relationship between extractable sulphur (ppm) and relative yields (Extractant - Morgan's Reagent,soil-Alluvial)**

12

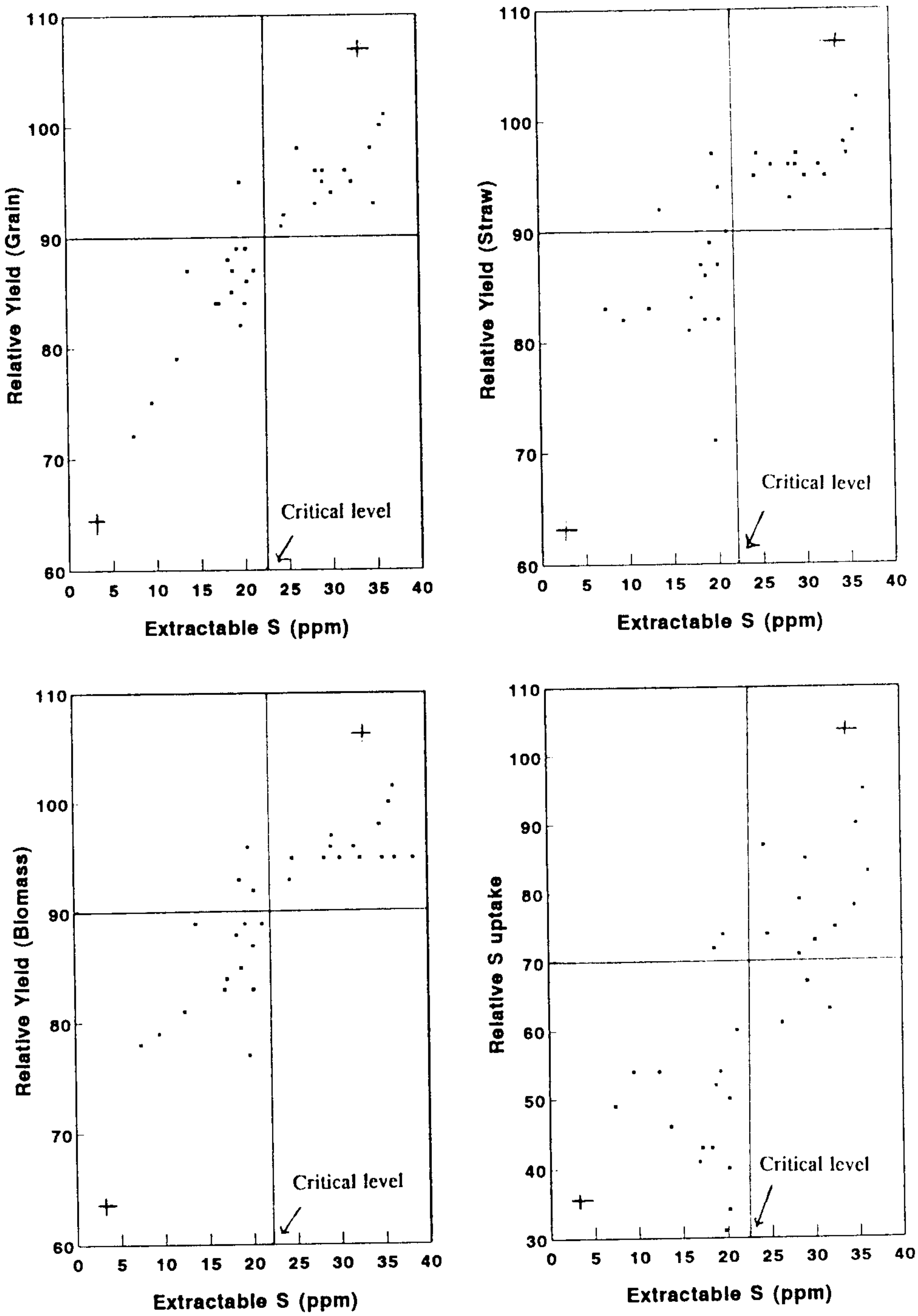


Fig. 13. Relationship between extractable sulphur (ppm) and Relative yields (Extractant - Olsen's Reagent, soil-Alluvial)

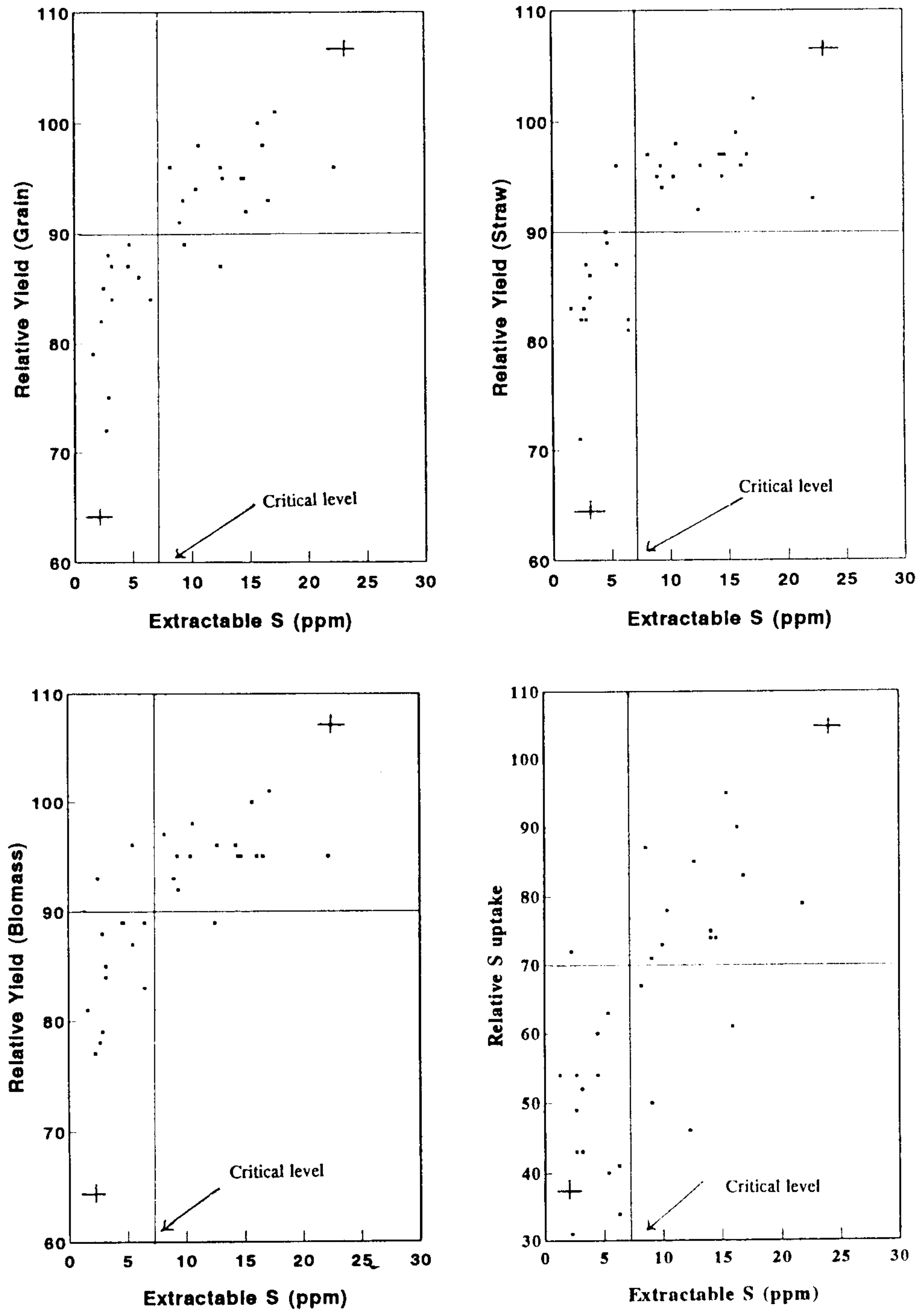


Fig. 14. **Relationship between extractable sulphur (ppm) and relative yields (Extractant - Ammonium chloride, soil-Alluvial)**

Table 12. Critical levels of S for different extractants (Alluvial soil)

Extractant	Range of available S (ppm)	Mean value (ppm S)	Median value (ppm S)	Critical level (ppm S)
1. Water	1.8-19.1	7.7	6.4	7
2. NaCl	3.2-24.1	8.9	8.2	8
3. NH_4OAc	3.2-25.0	13.8	13.5	13
4. $CaCl_2$	0.9-18.6	7.6	8.4	5
5. NH_4F + HCl	2.7-28.1	13.4	12.3	13
6. NH_4OAc + HOAc	2.3-29.1	14.7	13.6	15
7. $Ca(H_2PO_4)_2$	2.3-33.2	14.4	15.0	15
8. KH_2PO_4	3.2-39.1	16.3	17.9	15
9. $Ca(H_2PO_4)_2$ + HOAc	2.3-29.1	13.7	14.1	15
10. NaOAc + HOAc	2.7-26.8	14.1	11.8	11
11. $NaHCO_3$	7.3-35.9	23.2	20.4	22
12. NH_4Cl	1.3-21.8	8.7	8.8	7
Mean	2.7-27.5	13.0	12.5	12.2

Table 13. Responsiveness of rice to sulphur (Alluvial)

Extractants	Critical level (ppm S)	Respons-iveness	No. of samples	Grain yield (g) without S	Grain yield (g) with S	Increase of grain yield (%)
1. Water	7	Resp.	16	12.83	15.55	21.2
		Nonresp.	14	14.72	15.56	5.7
2. NaCl	8	Resp.	15	12.61	14.86	17.8
		Nonresp.	15	15.02	14.75	-1.8
3. NH_4OAc	13	Resp.	15	12.57	14.79	17.7
		Nonresp.	15	15.06	14.82	-1.6
4. $CaCl_2$	5	Resp.	13	12.04	15.85	31.6
		Nonresp.	17	14.24	14.77	3.7
5. NH_4F + HCl	13	Resp.	18	12.61	14.98	18.8
		Nonresp.	12	15.62	14.97	-4.1
6. NH_4OAc + HOAc	15	Resp.	16	12.40	17.09	37.8
		Nonresp.	14	14.53	14.64	0.76
7. $Ca(H_2PO_4)_2$	15	Resp.	15	12.70	14.92	17.5
		Nonresp.	15	14.79	14.69	-0.1
8. KH_2PO_4	15	Resp.	12	11.92	14.36	20.5
		Nonresp.	18	15.68	16.02	2.10
9. $Ca(H_2PO_4)_2$ + HOAc	15	Resp.	16	12.23	14.36	17.4
		Nonresp.	14	15.62	15.79	1.1
10. NaOAc + HOAc	11	Resp.	13	11.87	14.10	18.8
		Nonresp.	17	15.30	16.31	6.6
11. $NaHCO_3$	22	Resp.	16	12.44	14.64	17.7
		Nonresp.	14	15.39	16.17	5.1
12. NH_4Cl	7	Resp.	14	12.25	14.57	18.9
		Nonresp.	16	15.18	16.04	5.7
Mean	12.2	Resp.	14.9	12.4	15.0	21.5
		Nonresp.	15.1	15.1	15.4	1.9

4.2.3 Estimation of S by different methods - Brown hydromorphic soils

The quantities of S extracted by different extractants from soils of different locations in the state having brown hydromorphic rice soils are presented in Table 14. The mean values of available sulphur extracted by different extractants show that out of 30 locations 16 fall in low category of S level (< 10 ppm), 5 in medium level (10 to 15 ppm) and 9 locations fall in high level category. The highest mean value of S is recorded in location B.29 (Poomodupadam in Palakkad district) and the lowest mean value of 2.4 ppm is in B.23 (Dhoni, Palakkad). This soil shows less than 5 ppm (low) under all methods of extractions studied.

The coefficients of correlation between different methods in brown hydromorphic soil are presented in Table 15. It is seen that the estimation methods have significant correlation among themselves. Water has highest correlation with sodium chloride followed by monocalcium phosphate.

Sodium chloride has highest correlation to calcium chloride. Ammonium acetate has highest correlation to ammonium chloride followed by potassium dihydrogen orthophosphate, calcium chloride and sodium chloride. Calcium chloride has significant correlation with sodium chloride, Morgan's reagent and ammonium acetate. Brays extractant has the highest correlation with potassium dihydrogen orthophosphate followed by ammonium acetate + acetic acid. Ammonium acetate + acetic acid has higher correlation with potassium dihydrogen orthophosphate and monocalcium phosphate. Monocalcium phosphate has highest correlation with potassium dihydrogen orthophosphate and ammonium acetate + acetic acid. Similarly potassium dihydrogen orthophosphate has highest correlation with monocalcium

Table 14. Sulphur extracted (ppm) by extractants (brown hydromorphic soil)

Location No.	Water A	NaCl B	NH_4OAc C	$CaCl_2$ D	NH_4F + HCl E	NH_4OAc + HOAc F	$Ca(H_2PO_4)_2$ G
B.1	8.4	7.4	6.2	4.2	14.2	13.2	12.3
B.2	16.2	18.5	32.2	18.4	22.3	28.5	45.4
B.3	4.3	6.6	14.3	2.3	5.1	15.3	14.2
B.4	4.4	8.7	16.4	10.4	7.2	15.4	14.3
B.5	4.3	7.6	3.3	2.7	6.3	12.2	20.4
B.6	11.2	16.7	19.4	17.1	26.2	15.3	16.2
B.7	2.4	2.5	4.0	2.2	9.2	14.4	11.4
B.8	4.3	7.7	7.0	2.3	10.3	11.2	14.7
B.9	5.2	12.2	9.4	7.2	12.4	14.3	14.4
B.10	2.1	4.5	5.2	11.5	14.2	12.2	8.8
B.11	9.2	17.4	21.1	16.2	8.5	24.1	31.2
B.12	7.3	16.3	18.2	13.4	15.6	24.2	19.2
B.13	1.4	3.7	1.3	0.8	5.4	2.2	4.2
B.14	15.2	17.6	14.0	10.4	12.2	22.1	23.3
B.15	6.3	9.3	4.2	2.5	7.2	7.1	9.4
B.16	14.5	13.4	12.5	6.7	12.3	14.1	24.5
B.17	5.2	14.2	7.2	5.6	9.0	8.2	15.4
B.18	4.2	3.4	4.3	5.2	8.2	8.2	13.6
B.19	3.2	3.5	1.5	4.3	7.0	4.1	8.7
B.20	3.2	4.3	2.1	5.4	5.1	6.0	12.8
B.21	5.2	5.4	4.2	7.7	6.2	9.1	12.8
B.22	7.0	6.2	3.3	5.6	8.2	8.1	12.9
B.23	1.3	1.5	1.4	1.7	1.6	1.4	3.2
B.24	8.2	6.2	8.2	4.2	12.2	11.1	12.1
B.25	10.1	17.1	26.1	9.2	25.3	27.3	35.2
B.26	3.2	4.2	16.2	6.3	9.4	14.1	11.3
B.27	4.1	7.4	12.4	4.1	5.6	11.2	4.2
B.28	7.2	3.3	4.3	3.2	6.5	7.3	6.2
B.29	17.1	26.1	32.0	24.1	30.7	31.2	44.1
B.30	18.2	37.2	46.1	37.0	20.2	26.4	33.2

Contd.

Table 14. Continued

Location No.	KH_2PO_4 H	$Ca(H_2PO_4)$+ HOAc I	NaOAc+ HOAc J	$NaHCO_3$ K	NH_4Cl L	Mean
B.1	14.2	3.2	17.5	12.4	17.5	10.9
B.2	38.3	19.2	37.2	46.3	29.2	29.3
B.3	17.4	6.3	12.1	16.7	17.3	11.0
B.4	14.2	8.4	10.7	30.4	19.4	13.3
B.5	14.2	4.2	15.2	12.8	4.3	8.9
B.6	18.3	11.3	29.1	38.2	17.4	19.7
B.7	14.2	8.4	9.2	18.2	2.2	8.2
B.8	14.0	3.7	21.1	10.3	7.2	9.5
B.9	13.0	8.2	26.2	18.3	17.2	13.2
B.10	13.1	6.3	21.3	6.5	11.3	9.7
B.11	33.2	16.3	40.4	28.4	24.7	22.6
B.12	26.1	9.4	14.2	34.7	11.2	17.5
B.13	3.2	6.2	9.3	5.6	5.2	4.0
B.14	12.2	10.2	17.4	26.6	16.4	16.5
B.15	8.3	7.4	7.4	6.2	8.2	6.9
B.16	16.4	8.2	17.7	28.3	14.2	15.2
B.17	12.2	9.4	4.2	12.1	4.2	8.9
B.18	8.4	2.5	6.3	12.0	6.3	6.9
B.19	6.4	2.7	4.3	8.2	3.5	4.8
B.20	11.0	4.8	6.2	8.2	4.6	6.1
B.21	13.2	8.2	15.1	12.2	2.2	8.5
B.22	11.1	6.6	2.0	10.4	2.7	7.0
B.23	3.2	2.9	4.0	4.3	2.6	2.4
B.24	9.3	8.0	6.2	10.2	5.2	8.4
B.25	36.2	19.0	19.1	32.5	29.1	23.8
B.26	18.2	16.2	11.2	22.1	9.2	11.8
B.27	5.7	5.1	4.5	18.7	5.3	7.3
B.28	6.2	4.2	6.2	18.3	4.2	6.4
B.29	50.3	48.1	49.2	48.0	46.3	37.3
B.30	43.2	34.2	56.3	49.2	42.4	37.0

phosphate and ammonium acetate acetic acid. Monocalcium phosphate + acetic acid has highest correlation with potassium dihydrogen orthophosphate. Morgan's reagent has the highest correlation with calcium chloride and ammonium chloride. Olsen's reagent has the highest correlation with ammonium acetate and potassium dihydrogen orthophosphate. Ammonium chloride has the highest correlation with ammonium acetate and potassium dihydrogen orthophosphate. In general the correlations between the extractants shows that potassium dihydrogen orthophosphate has high correlation with most other extractants in brown hydromorphic soils.

4.2.4 Identification of suitable S estimation procedure - Brown hydromorphic soil

The relative yields of grain, straw and biomass and relative uptake of sulphur are presented in Table 16. The relative grain yield ranged between 69.1 and 102 and the relative straw yield ranged between 70.3 and 99.2. The relative uptake of nutrient ranged between 33 and 91 and the relative biomass yield ranged between 69.5 and 100.1.

The Figures 15 to 26 show scatter diagrams of relative yields and content of available sulphur estimated in 30 locations of brown hydromorphic soil by different extractants. The critical levels of sulphur are estimated by Cate and Nelson procedure as seen in the figures.

Coefficients of correlation between different relative yield parameters and methods of estimation are presented in Table 17. With regard to relative grain yield correlation is highest with ammonium acetate + acetic acid followed by monocalcium phosphate. The correlation of relative straw yield is highest with ammonium acetate + acetic acid followed by water and ammonium chloride. Relative uptake of

Table 15. Coefficients of correlation between different methods
(Brown hydromorphic soil)

Sl. No.	Methods	B	C	D	E	F	G	H	I	J	K	L
A	Water	0.8480**	0.7806**	0.7526**	0.7385**	0.7543**	0.8101**	0.7302**	0.7087**	0.7102**	0.6853**	0.7388**
B	NaCl		0.8870**	0.8980**	0.7273**	0.8023**	0.8115**	0.8360**	0.8090**	0.8413**	0.7406**	0.8534**
C	NH_4OAC			0.8873**	0.7309**	0.8770**	0.8085**	0.8983**	0.8319**	0.8336**	0.8180**	0.9004**
D	$CaCl_2$				0.7033**	0.7524**	0.7217**	0.8293**	0.8180**	0.8755**	0.7307**	0.8367**
E	NH_4F + HCl					0.7698**	0.7449**	0.7796**	0.7363**	0.6823**	0.6746**	0.7689**
F	NH_4OAc+ HOAc						0.8824**	0.9156**	0.7607**	0.7742**	0.7301**	0.8527**
G	$Ca(H_2PO_4)$							0.9178**	0.7804**	0.7496**	0.6859**	0.8145**
H	KH_2PO_4								0.8867**	0.8303**	0.7311**	0.8976**
I	$Ca(H_2PO_4)$+ HOAc									0.7518**	0.7259**	0.8645**
J	NaOAc + HOAc										0.7010**	0.8551**
K	$NaHCO_3$											0.7462**
L	NH_4Cl											-

* Significant at 5% level
**Significant at 1% level

Table 16. Relative yield parameters (Brown hydromorphic soil)

Sample No.	Relative grain yield (%)	Relative straw yield (%)	Relative uptake of S (%)	Relative total biomass yield (%)
1.	72.0	91.7	72.0	92.7
2.	100.2	96.2	68.5	98.2
3.	94.3	89.5	75.0	92.0
4.	95.1	90.1	70.0	92.0
5.	89.0	86.2	69.0	87.5
6.	95.2	98.1	81.0	86.5
7.	85.9	82.1	56.5	84.0
8.	87.1	88.3	60.0	87.0
9.	92.2	89.2	75.0	90.7
10.	89.5	91.1	67.0	90.3
11.	99.8	97.1	91.0	98.5
12.	81.0	81.2	64.0	81.1
13.	76.1	75.2	41.0	75.7
14.	93.2	96.2	71.5	94.7
15.	81.0	84.1	64.5	82.6
16.	94.1	93.0	67.0	93.6
17.	87.9	85.0	52.5	86.5
18.	83.2	85.6	38.0	84.4
19.	82.1	82.4	38.0	82.3
20.	84.9	84.4	46.0	84.7
21.	87.0	88.1	69.5	87.6
22.	84.0	81.2	71.0	82.6
23.	69.1	70.3	33.0	69.5
24.	83.5	90.2	65.0	86.7
25.	100.1	99.2	79.0	99.5
26.	85.0	92.3	72.5	88.5
27.	84.1	86.1	68.0	85.0
28.	82.0	85.1	39.5	83.5
29.	102.0	98.2	87.0	100.1
30.	101.1	95.0	86.0	97.5

Table 17. Coefficients of correlation between soil test values (ppm S) obtained by different methods and yield parameters (Brown hydromorphic soil)

Sl. No.	Methods	Relative grain yield	Relative straw yield	Relative uptake of sulphur	Relative total biomass production	Grain yield	S-content in grain	Straw yield	S-content in straw
A	Water	0.7070**	0.6963**	0.5750**	0.6893**	0.2506	0.5315**	0.0212	0.5102**
B	NaCl	0.7284**	0.6220**	0.6469**	0.6605**	0.2324	0.5972**	0.0196	0.5388**
C	NH_4OAc	0.7576**	0.6573**	0.6731**	0.6795**	0.1807	0.6110**	0.1309	0.5049**
D	$CaCl_2$	0.6782**	0.5660**	0.5957**	0.5690**	0.2451	0.5421**	0.1416	0.4907**
E	NH_4F + HCl	0.6841**	0.6875**	0.5757**	0.5957**	0.1085	0.5482**	0.1072	0.5587**
F	NH_4OAc+ HOAc	0.8235**	0.7266**	0.7477**	0.7770**	0.1875	0.6049**	0.1654	0.5465**
G	$Ca(H_2PO_4)_2$	0.8181**	0.6782**	0.6034**	0.7673**	0.3017	0.5625*	0.1300	0.4322*
H	KH_2PO_4	0.7884**	0.6480**	0.6828**	0.7234**	0.2311	0.6246*	0.1325	0.4789*
I	$Ca(H_2PO_4)_2$+ HOAc	0.6444**	0.5591**	0.5927**	0.6115**	0.2941	0.5114*	0.0520	0.4064*
J	NaOAc + HOAc	0.7719**	0.6563**	0.6969**	0.6742**	0.1577	0.6110*	0.1308	0.5559*
K	$NaHCO_3$	0.5900**	0.4417*	0.4644**	0.4422**	0.1383	0.4675*	0.2139	0.3914*
L	NH_4Cl	0.8132**	0.6938**	0.6808**	0.7591**	0.1377	0.5966*	0.0708	0.5127*

* Significant at 5% level
** Significant at 1% level

sulphur as well as relative total biomass are highly correlated with ammonium acetate + acetic acid.

The ranges of available sulphur, mean and median values under different methods of estimation and critical concentrations of available sulphur found out from the scatter diagrams are presented in Table 18.

The mean range of available sulphur and the mean critical concentration of brown hydromorphic soils are 1.8 to 41.2 ppm and 12.6 ppm respectively. The overall means of mean values and median values are 13 ppm and 10.5 ppm respectively. Water extracted the closed range of available sulphur 0.9 to 18.2 ppm and the widest range was extracted by Morgan's reagent. The highest level of critical concentration is 20 ppm extractable by Olsen's reagent and the lowest critical concentration is 6 ppm (water). The critical concentration of available S in brown hydromorphic soil is 10 ppm when extracted by sodium chloride, calcium chloride, Bray's reagent and monocalcium phosphate + acetic acid. The critical levels are 17, 16 and 16 respectively for monocalcium phosphate, potassium dihydrogen orthophosphate and Morgan's reagent which fall in high category under conventional methods of grouping in to sufficiency and deficiency. The highest mean value and median value are observed when extracted with Olsen's reagent.

Response of rice to addition of sulphur in various soils has been determined and presented in Table 19. The mean number of responsive soils and non responsive soils are 19 and 11 in brown hydromorphic soil. The responsive soils gave an increase in yield to the level of 17.2 per cent, whereas, the non-responsive soils gave a mean increase of 5.9 per cent grain yield by application S @ 40 kg ha^{-1} over control. A comparatively same level of yield increase with the above mean

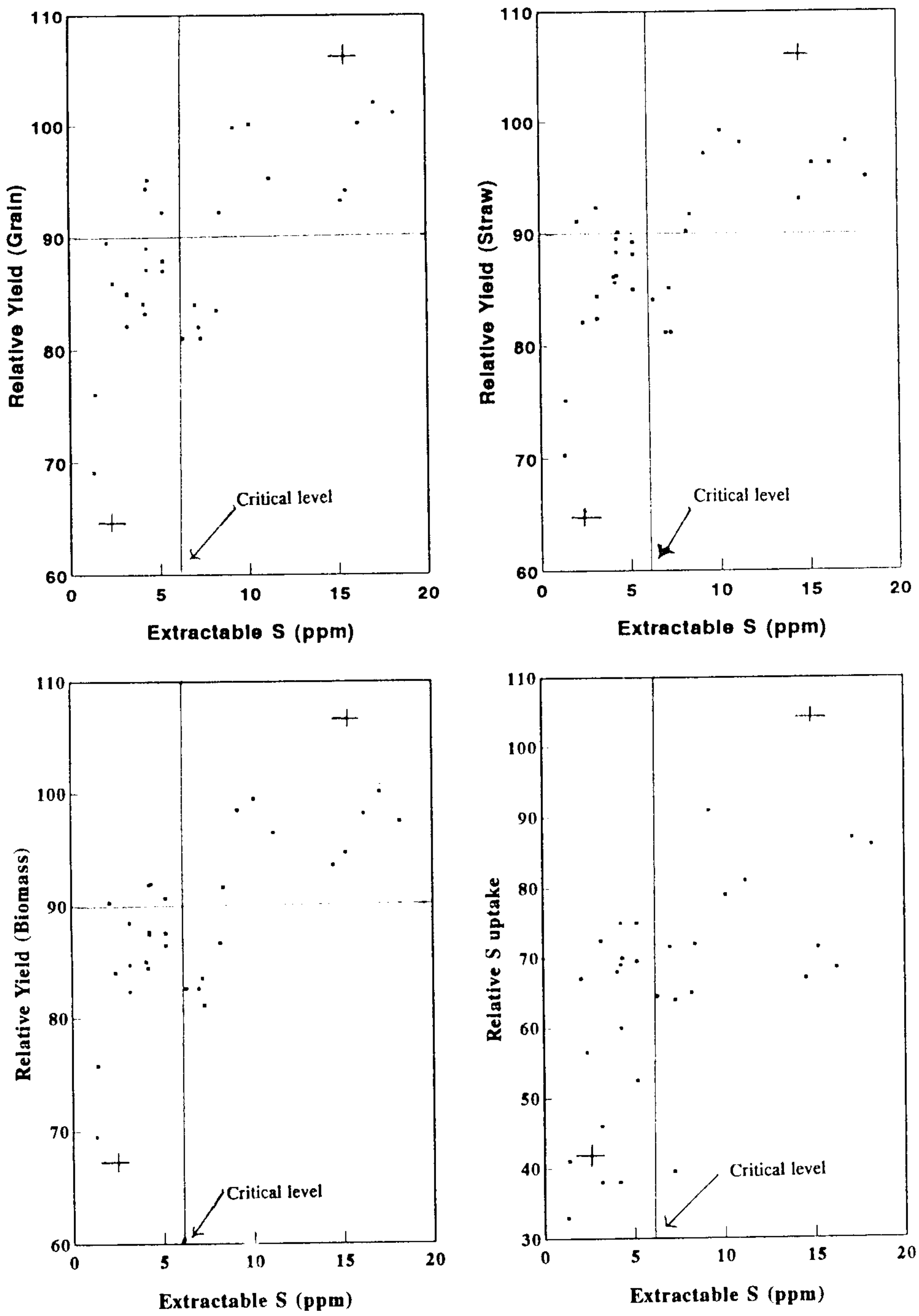


Fig. 15. **Relationship between extractable sulphur (ppm) and Relative yields (Extractant - Water ; Brown hydromorphic soil)**

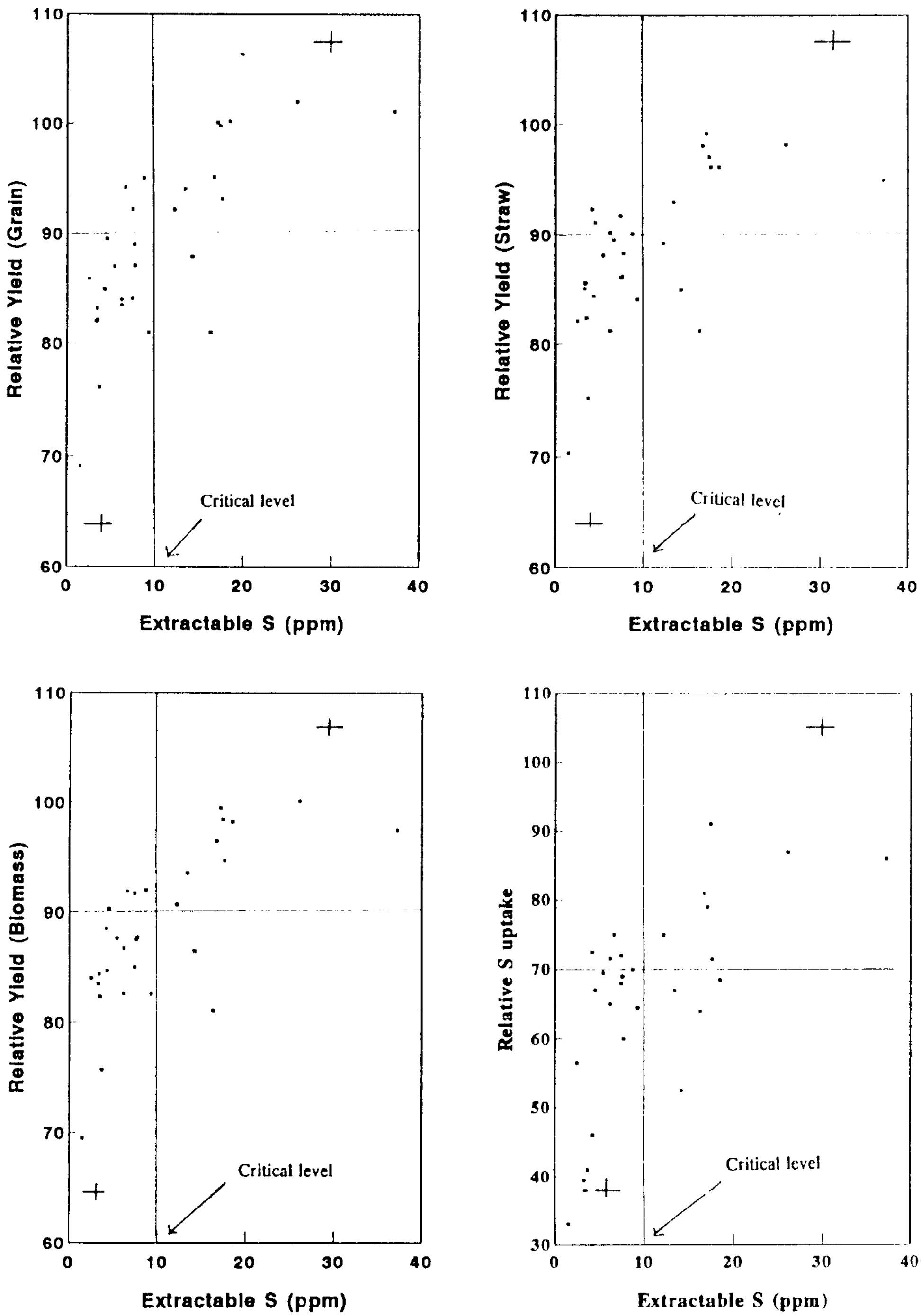


Fig. 16. **Relationship between extractable sulphur (ppm) and Relative yields (Extractant - Sodium Chloride ; Brown hydromorphic soil)**

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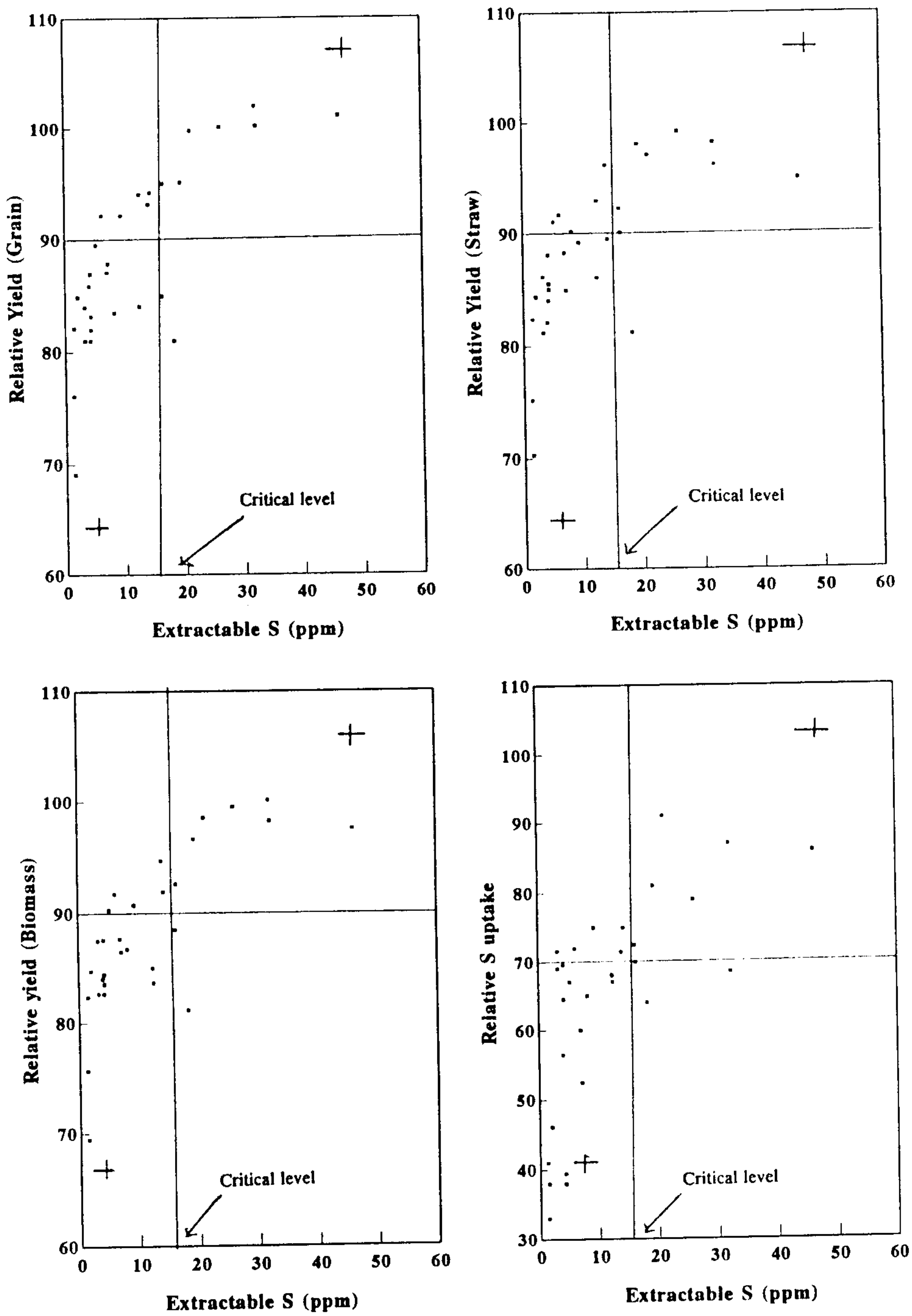

Fig. 17. Relationship between extractable sulphur (ppm) and relative yields (Extractant - Ammonium Acetate ; Brown hydromorphic soil)

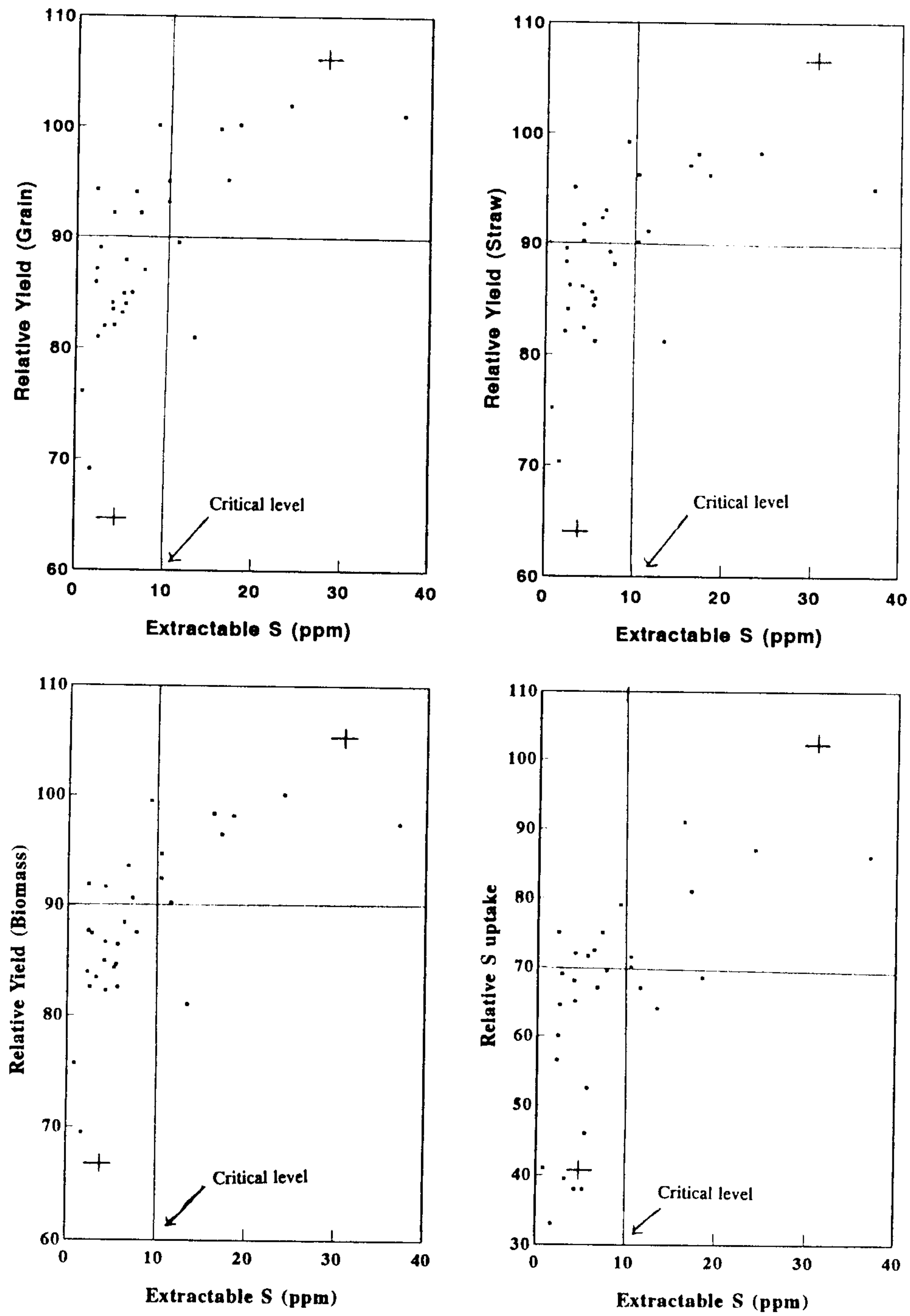

Fig. 18. Relationship between extractable sulphur (ppm) and Relative Yields (Extractants - Calcium chloride ; Brown hydromorphic soil)

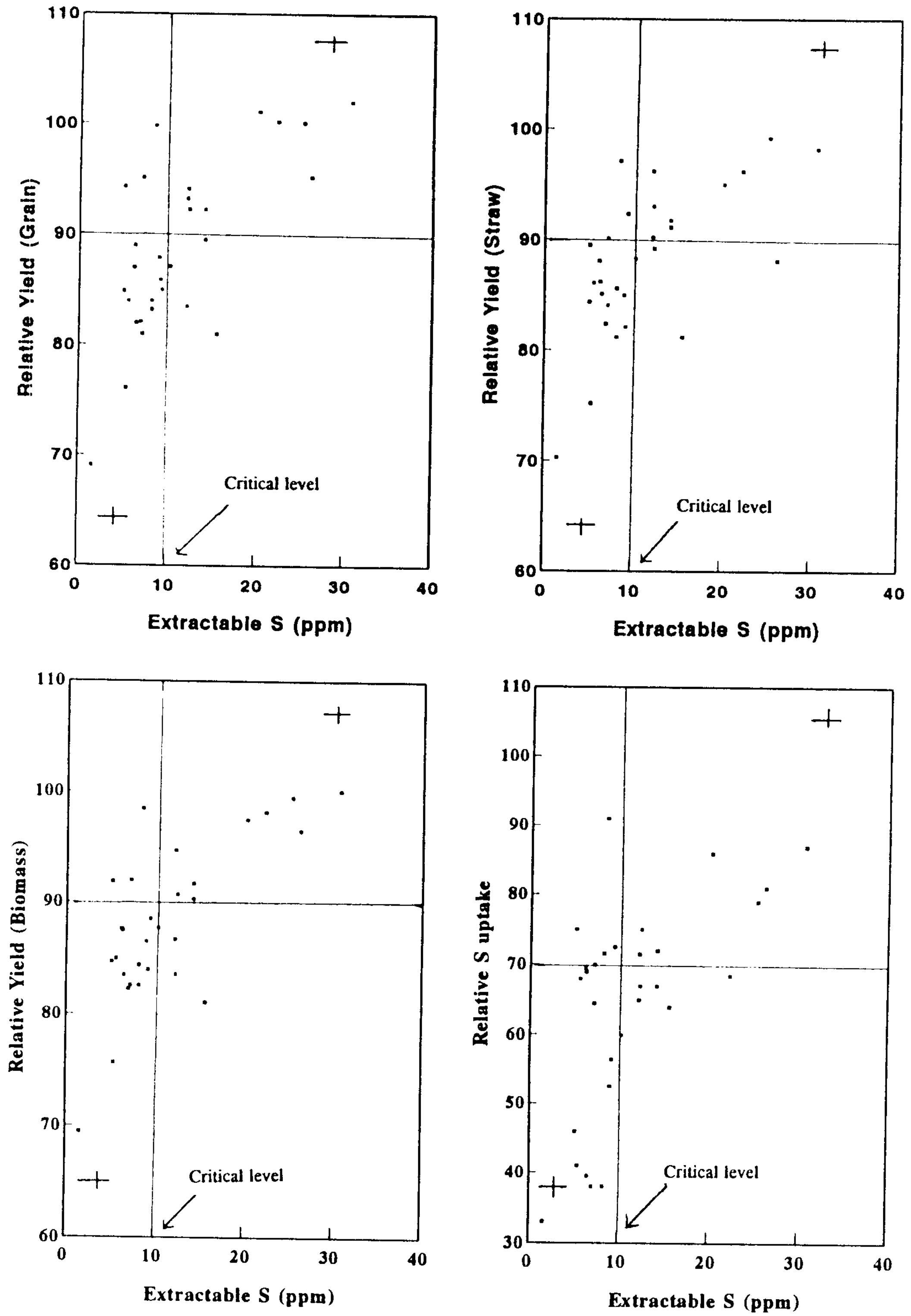

Fig. 19. Relationship between extractable sulphur (ppm) and Relative yields (Extractant - Bray's reagent No.1;Brown hydromorphic soil)

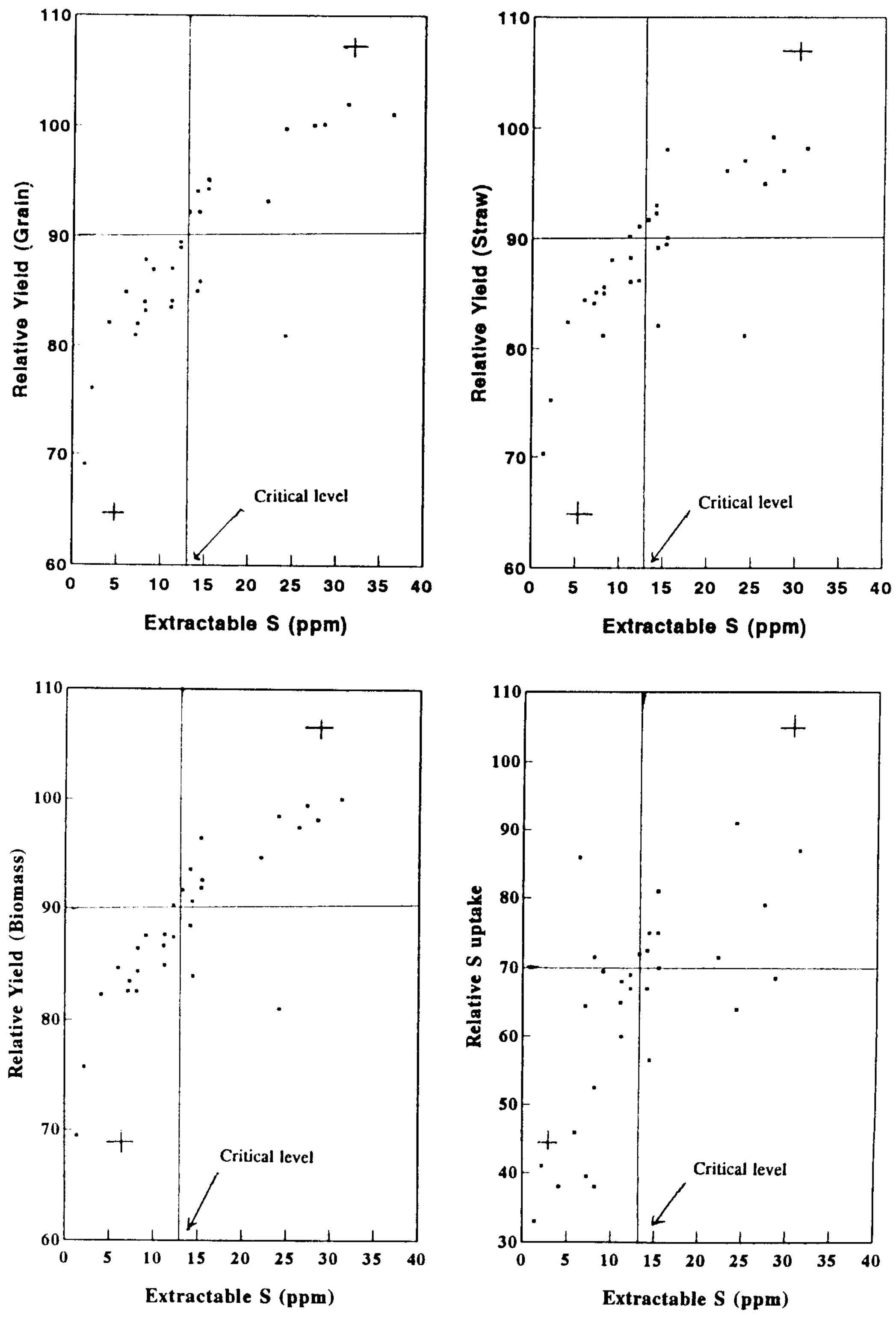

Fig. 20. **Relationship between extractable sulphur (ppm) and Relative yields (Extractant - Ammonium Acetate +Acetic acid; Brown hydromorphic soil)**

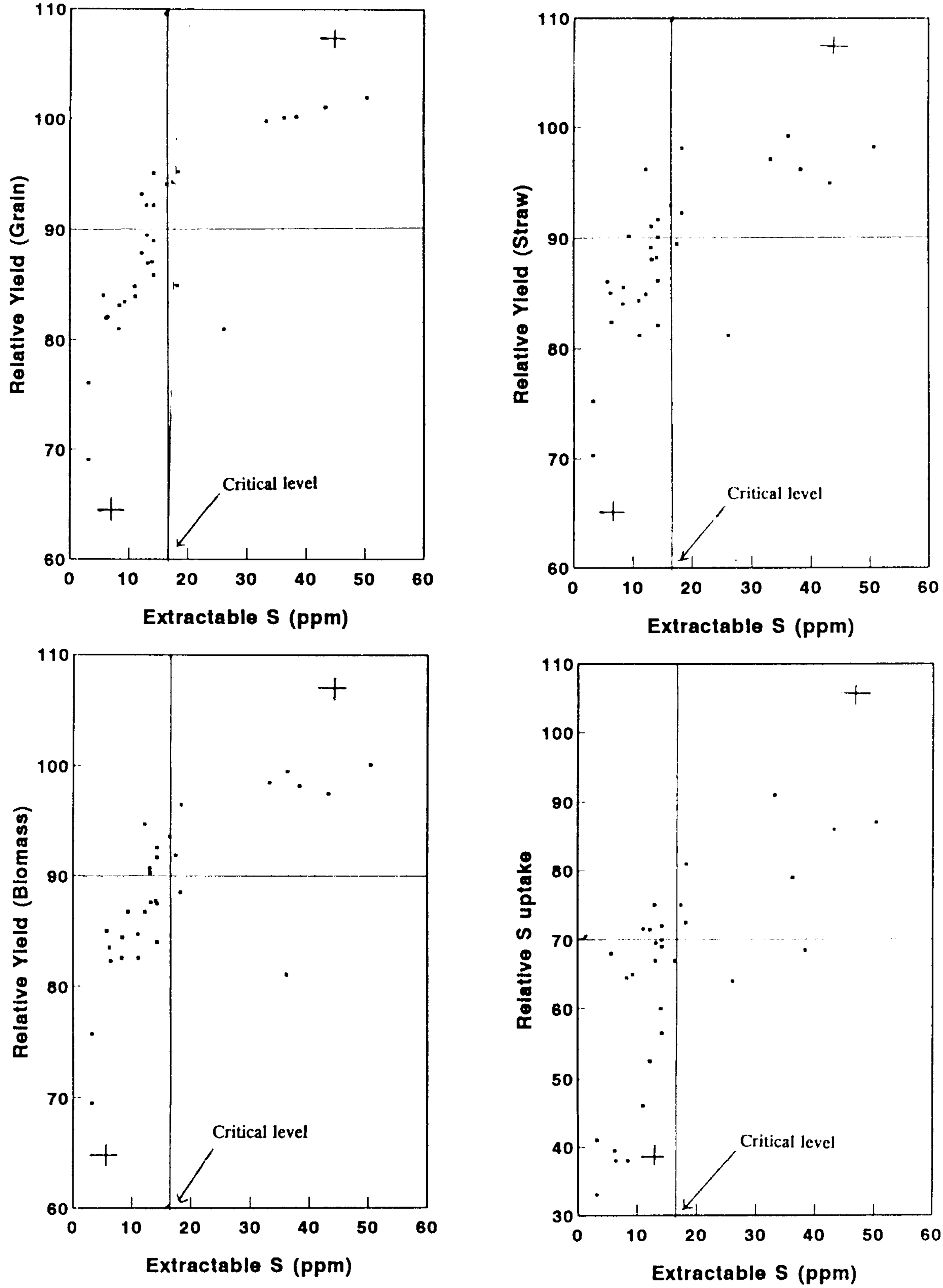

Fig.22. Relationship between extractable sulphur (ppm) and Relative yields
(Extractant - Potassium dihydrogen orthophosp ; Brown hydromorphic so

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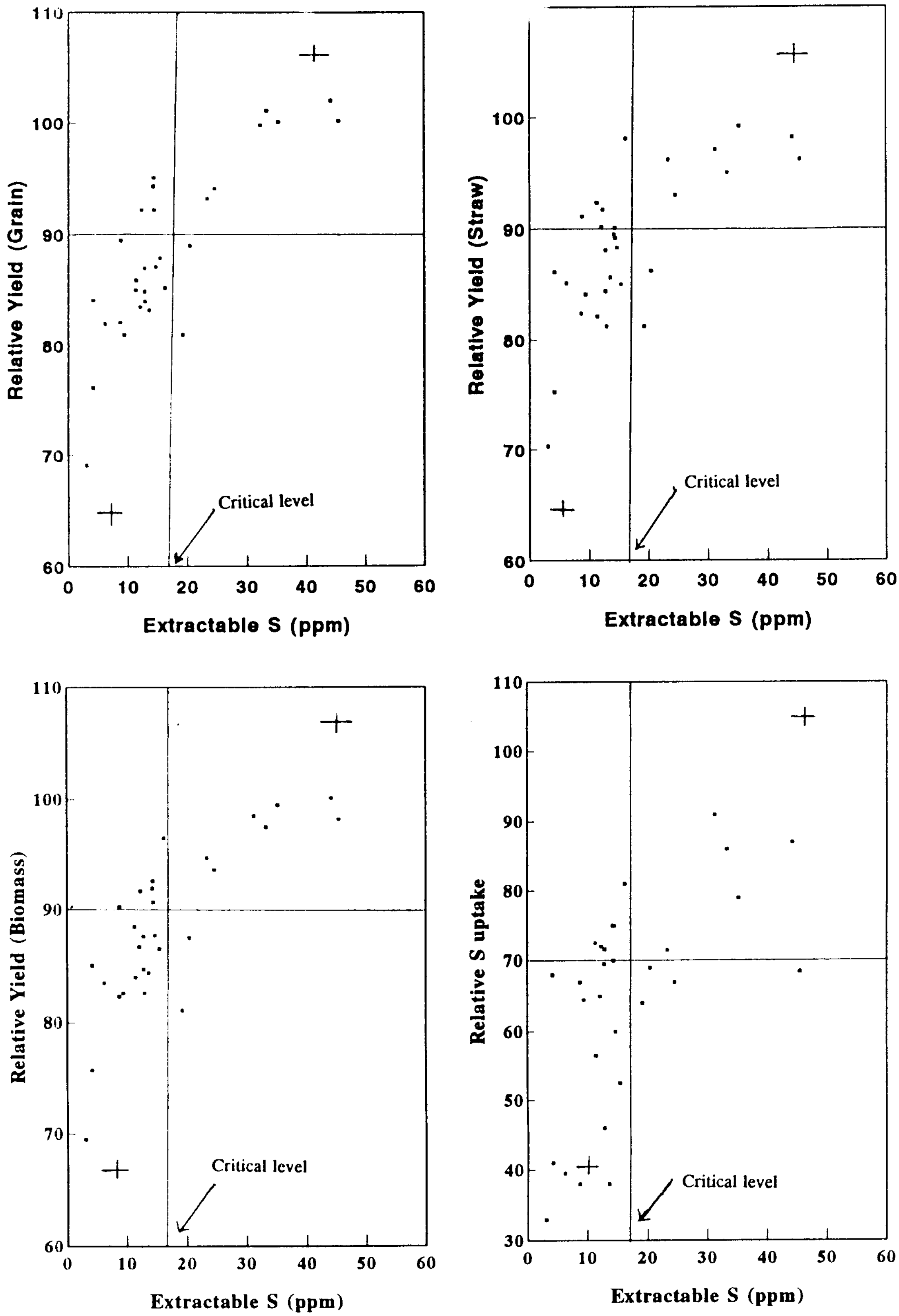

Fig. 21. Relationship between extractable sulphur (ppm) and relative yields (Extractant - Monocalcium phosphate ; Brown hydromorphic soil)

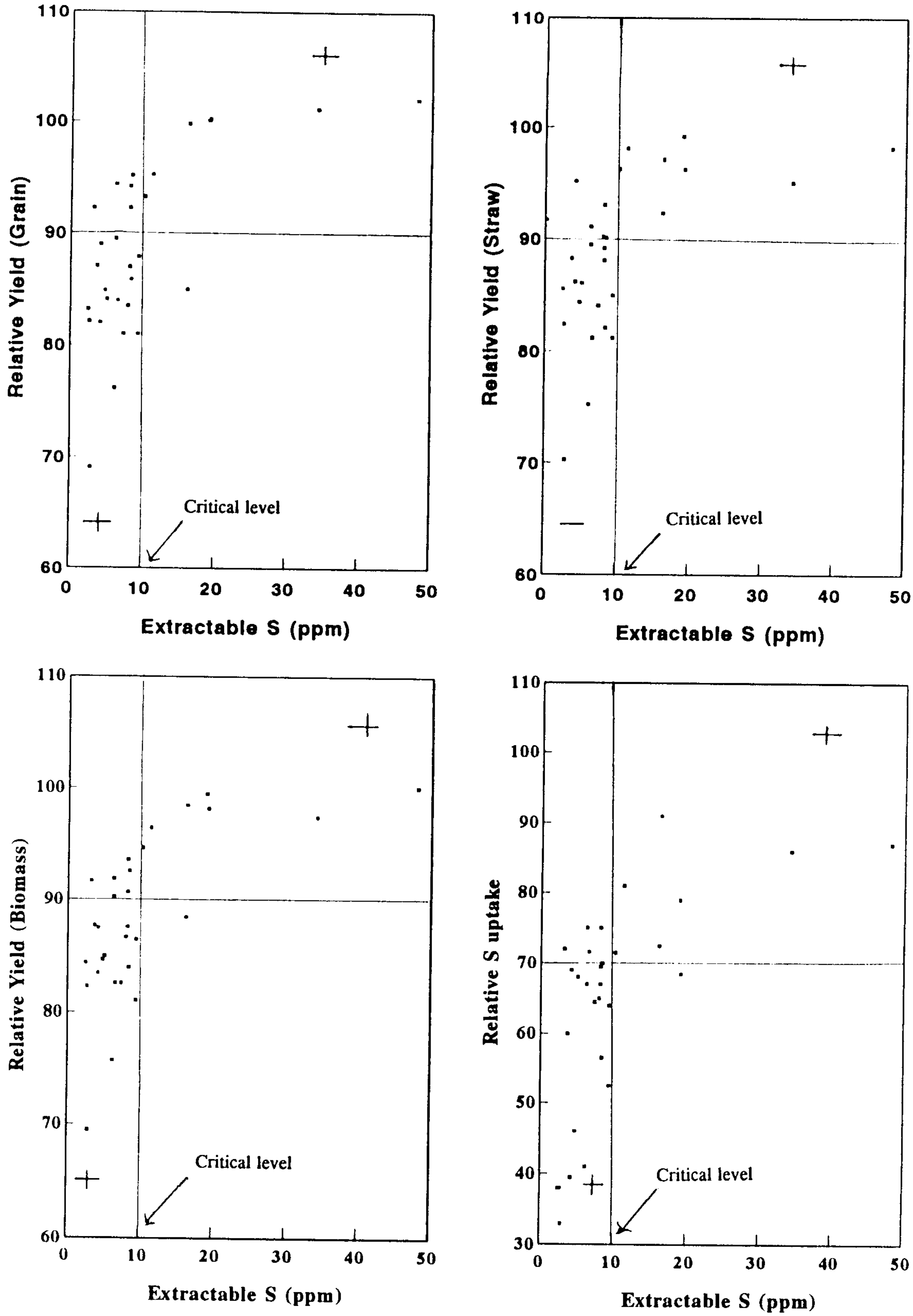

Fig. 23. Relationship between extractable sulphur (ppm) and Relative Yields (Extractant - Monocalcium phosphate + Acetic acid; Brown hydromorphic soil)

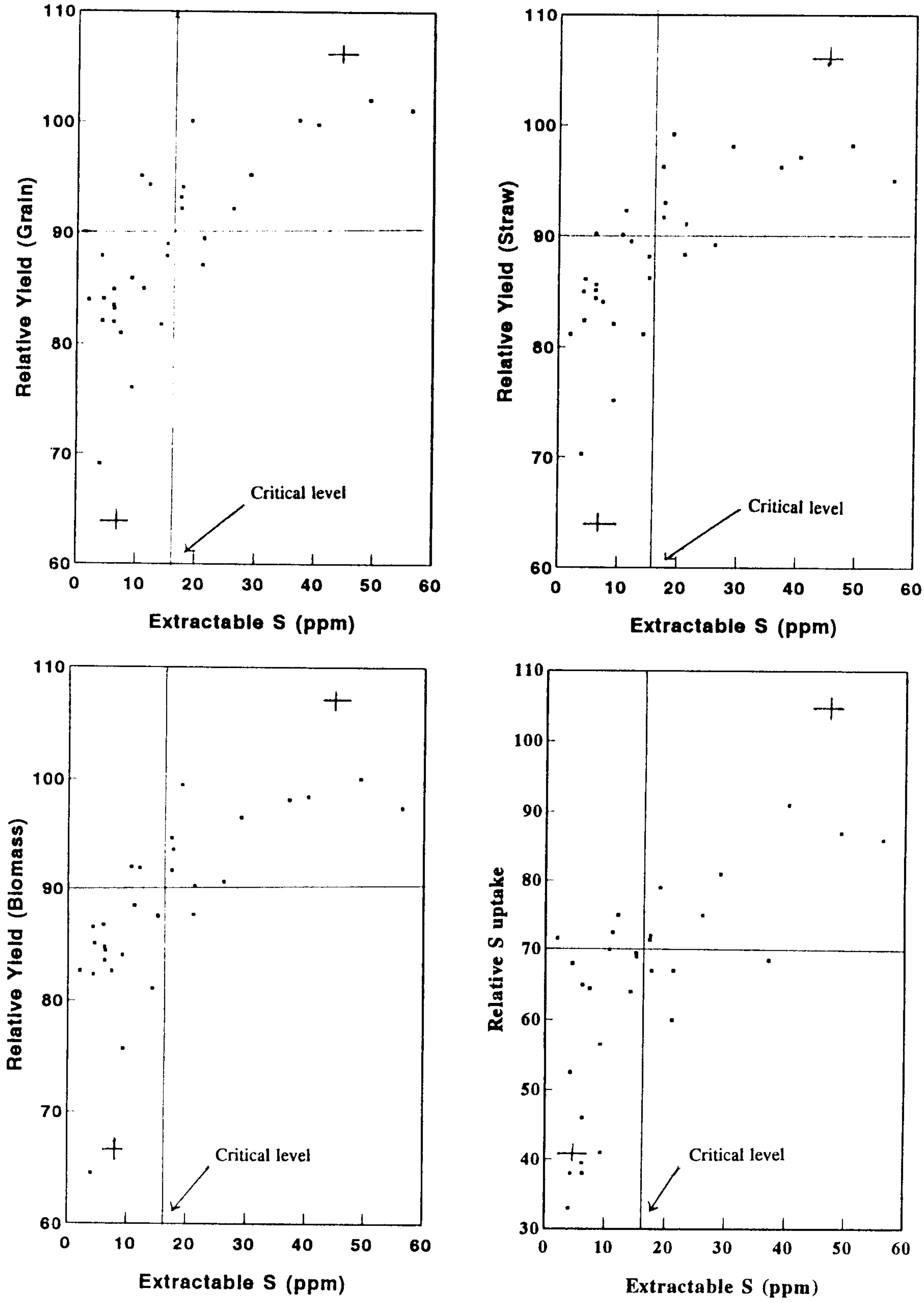

Fig. 24. Relationship between extractable sulphur (ppm) and Relative yields (Extractant - Morgan's reagent; Brown hydromorphic soil)

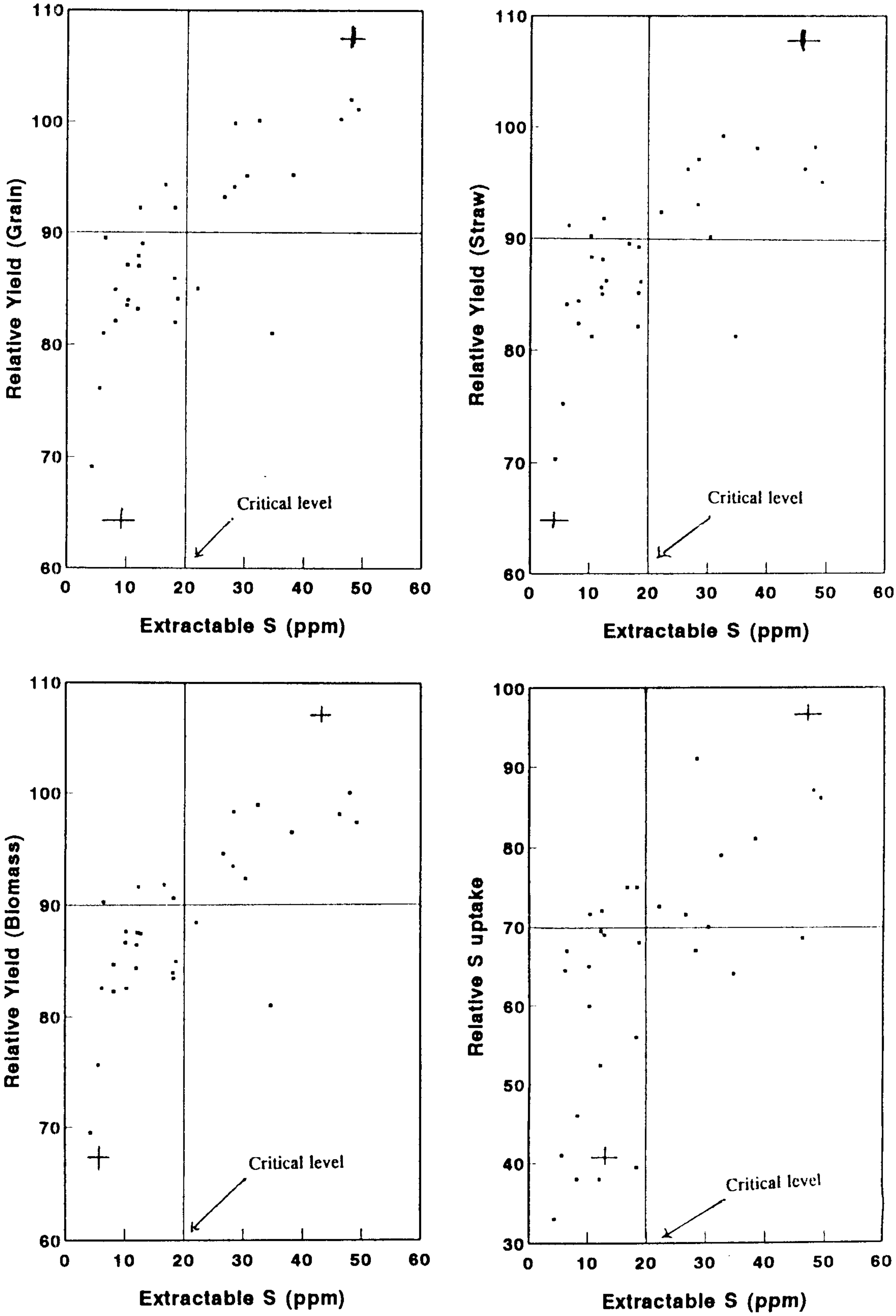

Fig. 25. Relationship between extractable sulphur (ppm) and relative yields (Extractant - Olsens'reagent ; Brown hydromorphic soil)

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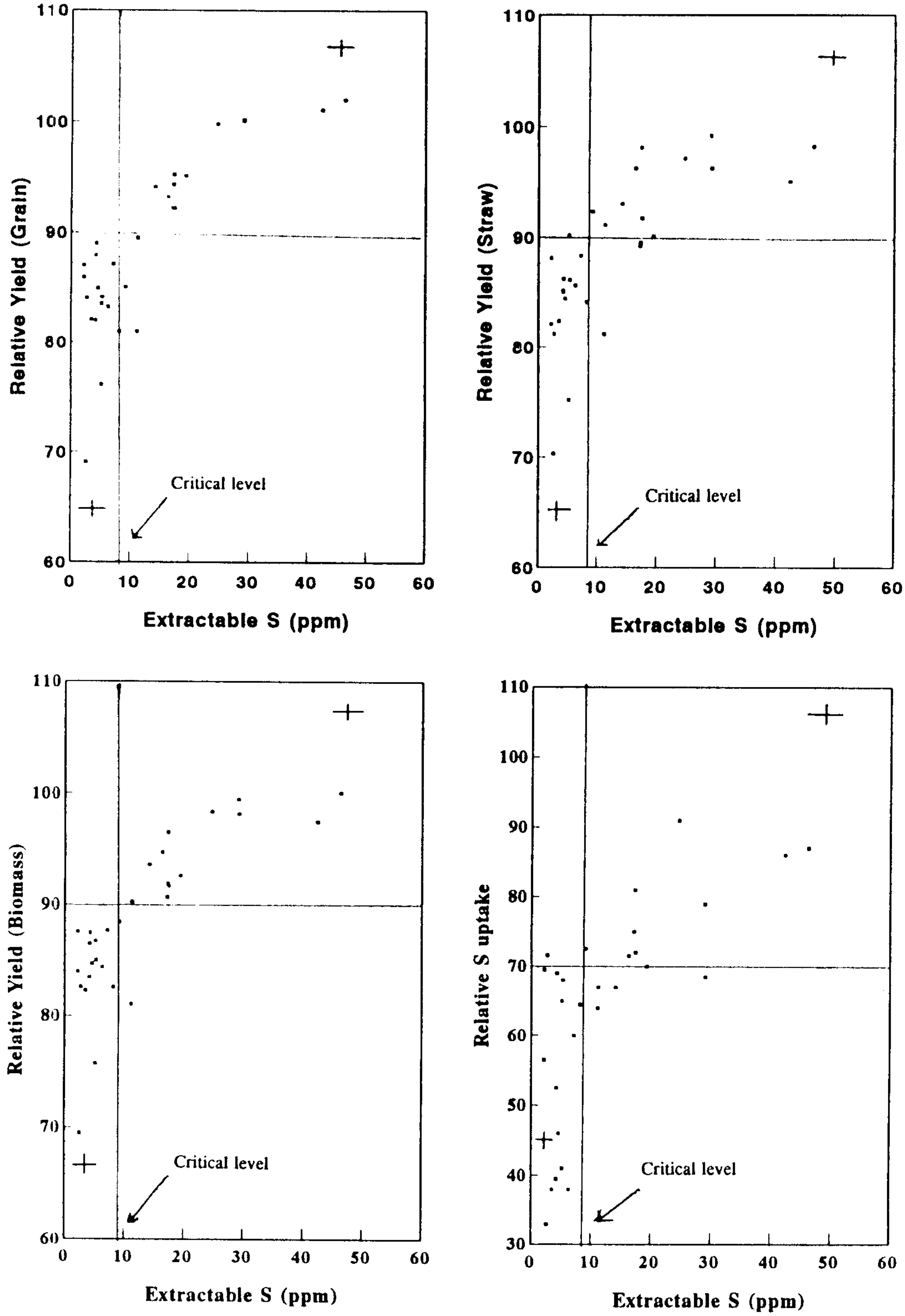


Fig. 26. Relationship between extractable sulphur (ppm) and Relative yields (Extractant - Ammonium chloride ; Brown hydromorphic soil)

Table 18. Critical levels of S for different extractants (Brown hydromorphic soil)

Extractant	Range of available S (ppm)	Mean value (ppm S)	Median value (ppm S)	Critical level (ppm S)
1. Water	0.9-18.2	7.0	5.0	6
2. NaCl	1.4-37.3	10.3	7.8	10
3. NH_4OAc	1.4-45.9	11.7	7.5	15
4. $CaCl_2$	0.9-36.8	8.3	5.5	10
5. NH_4F + HCl	1.3-30.4	11.4	8.9	10
6. NH_4OAc + HOAc	0.9-30.9	13.9	12.7	13
7. $Ca(H_2PO_4)_2$	2.3-45.0	16.9	14.1	17
8. KH_2PO_4	3.2-50.0	16.7	14.1	16
9. $Ca(H_2PO_4)_2$ + HOAc	2.3-48.2	10.1	8.9	10
10. NaOAc + HOAc	1.8-55.9	16.2	14.6	16
11. $NaHCO_3$	4.1-49.0	21.2	18.2	20
12. NH_4Cl	1.8-46.3	12.7	8.6	8
Mean	1.8-41.2	13.0	10.5	12.6

Table 19. Responsiveness of rice to sulphur (Brown hydromorphic)

Extractant	Critical level (ppm S)	Respons-iveness	No. of samples	Grain yield (g) per pot without S	Grain yield (g) per pot with S	Increase of grain yield (%)
1. Water	6	Resp.	16	11.80	13.81	17.0
		Nonresp.	14	11.73	12.62	7.6
2. NaCl	10	Resp.	19	11.21	12.67	13.0
		Nonresp.	11	12.73	13.35	4.8
3. NH_4OAc	15	Resp.	21	11.56	13.40	16.0
		Nonresp.	9	12.24	12.89	5.3
4. $CaCl_2$	10	Resp.	21	11.76	13.65	16.1
		Nonresp.	9	11.79	12.32	4.5
5. NH_4F + HCl	10	Resp.	17	12.46	13.83	10.9
		Nonresp.	13	11.04	11.39	5.3
6. NH_4OAc+HOAc	13	Resp.	15	11.55	13.64	18.1
		Nonresp.	15	12.05	12.89	6.9
7. $Ca(H_2PO_4)_2$	17	Resp.	21	11.42	13.32	16.6
		Nonresp.	9	12.57	13.09	4.2
8. KH_2PO_4	16	Resp.	20	11.38	13.24	16.4
		Nonresp.	10	12.55	13.26	5.7
9. $Ca(H_2PO_4)_2$+ HOAc	10	Resp.	22	11.78	14.45	22.7
		Nonresp.	8	10.43	10.85	4.0
10. NaOAc + HOAc	16	Resp.	18	11.56	13.65	18.3
		Nonresp.	12	12.08	12.61	4.4
11. $NaHCO_3$	20	Resp.	19	11.24	13.18	17.2
		Nonresp.	11	12.67	13.38	5.6
12. NH_4Cl	8	Resp.	14	11.68	13.80	18.2
		Nonresp.	16	11.90	12.77	7.3
Mean	12.6	Resp.	19	11.6	13.6	17.2
		Nonresp.	11	11.9	12.6	5.9

values are seen in the case of Olsen's reagent. However non-responsive soils have been more closely delineated by the extractants monocalcium phosphate + acetic acid, monocalcium phosphate, Morgan's extractant and calcium chloride. All these extractants therefore shows their acceptability as good extractants for estimation of sulphur in brown hydromorphic soils.

4.2.5 Relationship of available sulphur in soil with different plant nutrients in rice

Correlation coefficients between soil SO_4-S and N, P, K, Ca, Mg, Zn, Mn and Cu contents in rice plant in both alluvial soils and brown hydromorphic soils were studied in this experiment. In alluvial soils significant positive correlations were obtained between SO_4-S of soil and plant content of nitrogen and phosphorus. Presence of calcium and magnesium significantly correlated. In brown hydromorphic soil there were significant positive correlations between available sulphur and plant contents of N, P, K. Positive correlations were also seen between contents of P and K, Ca and Mg, mg and Zn.

4.2.6 Relationship between sulphur status and green algae

The correlations between soil SO_4-S, green algae presence (Plate 2), grain yield, relative biomass yield and grain sulphur content were studied in both the soil types, and presented in Table 21. It is seen that soil SO_4-S and green algae relationship is negative. Green algae has similar significant negative correlation with relative biomass yield, grain S content and straw S content. Relative biomass yield, soil SO_4-S, S content in straw and in grain are positively and significantly correlated to between themselves.

Table 20(a). Coefficients of correlation between available SO_4-S in soil and nutrient content in rice (Alluvial soil)

Contents	N %	P %	K %	Ca %	Mg %	Zn (ppm)	Mn (ppm)	Cu (ppm)	SO_4-S
1. N %		0.5003**	0.1864	-0.1140	0.1655	-0.0102	0.1720	-0.1575	0.6939**
2. P %			0.0190	-0.2687	-0.0113	-0.0743	-0.0478	0.0043	0.4954**
3. K %				-0.1310	0.0239	-0.0488	0.0431	-0.0250	0.1574
4. Ca %					0.5422**	-0.3254	-0.0315	0.0540	-0.2160
5. Mg %						-0.1453	-0.1026	-0.0802	-0.0081
6. Zn (ppm)							-0.2038	0.2645	-0.0031
7. Mn (ppm)								-0.0176	0.0328
8. Cu (ppm)									-0.1532
9. SO_4-S									

*Significant at 5% level
**Significant at 1% level

Table 20(b). Coefficients of correlation between available SO_4-S in soil and nutrient content in rice (Brown hydromorphic soil)

Contents	N%	P%	K%	Ca%	Mg%	Zn (ppm)	Mn (ppm)	Cu (ppm)	SO_4-S
1. N %		0.7682**	0.8845**	-0.0734	-0.0957	0.0120	-0.0083	0.1179	0.5529**
2. P %			0.8203**	0.0524	0.1236	0.2777	-0.3249	0.1123	0.5188**
3. K %				-0.0754	-0.0928	0.0613	-0.1519	0.0718	0.7261**
4. Ca %					0.6693**	0.2379	-0.5381	0.0542	-0.1036
5. Mg %						0.4228**	-0.6102	-0.0982	-0.0248
6. Zn (ppm)							-0.4798*	-0.0962	0.1234
7. Mn (ppm)								0.1582	-0.1027
8. Cu (ppm)									0.0380
9. SO_4-S									

*Significant at 5% level

**Significant at 1% level

Table 21. Coefficient of correlation between green algae and S status

Parameters	Green algae	Grain yield	Relative biomass yield	Grain S content	Straw S content
			A. Alluvial soil		
Soil SO_4-S	-0.3681*	0.5159*	0.4955*	0.4588*	0.4653*
Green algae		-0.1372	-0.4744*	-0.8307*	-0.7054*
Grain yield			0.3821*	0.3186	0.2064
Relative biomass yield				0.5035*	0.5441*
Grain S content					0.7240*
			B. Brown hydromorphic soil		
Soil SO_4-S	-0.6857*	0.2459	0.6091*	0.5781	0.6028
Green algae		0.0749	-0.5391*	-0.6746*	-0.8962
Grain yield			0.3911*	-0.0165	-0.1307
Relative biomass yield				0.6340*	0.4921*
Grain S content					0.7676*

* Significant at 5% level

Fig. 27. Relationship between relative yield of grain and sulphur content of plant at harvest (alluvial soil)

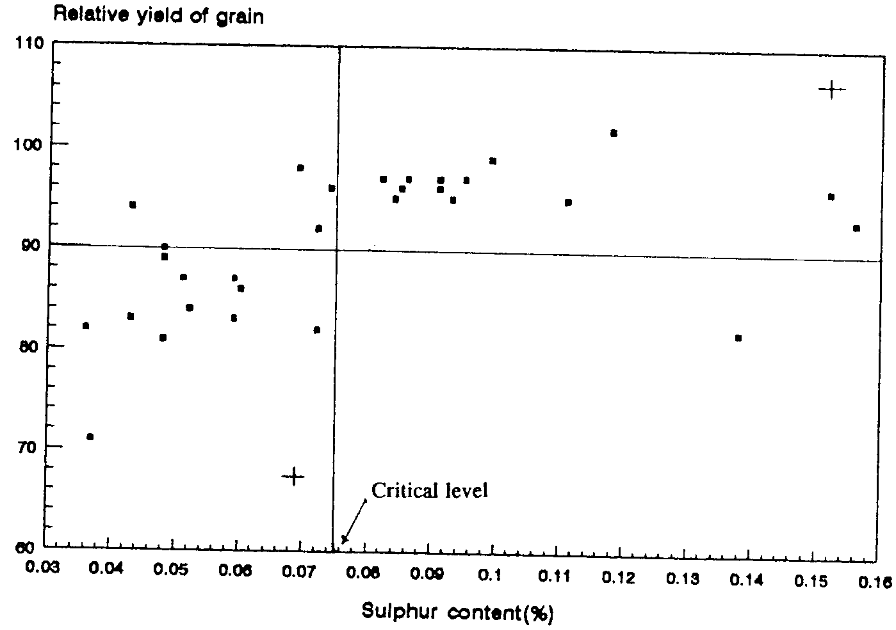
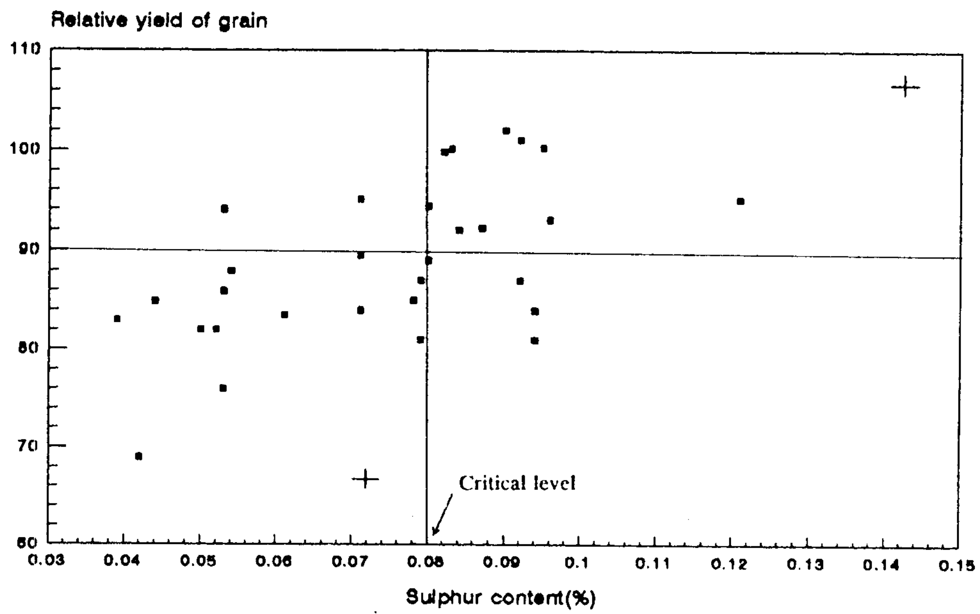


Fig. 28. Relationship between relative yield of grain and sulphur content of plant at harvest (brown hydromorphic soil)



4.2.7 Critical levels of S in rice at harvest

The relation between relative yield of grain and sulphur content in plant at harvest has been studied for both soils. The data has been plotted in a scatter diagram and the critical content of S in plant is estimated using Cate-Nelson procedure. From the Figures 27 and 28 it can be seen that for alluvial soil the critical sulphur content in straw at harvest is 0.075 per cent. In brown hydromorphic soil the critical sulphur content in straw at harvest is 0.08 per cent.

4.3 Part-III. Response of rice to different levels and sources of sulphur

Field experiments were conducted at Cropping System Research Centre, Karamana (Alluvial soil) and Regional Agricultural Research Station, Pattambi (Brown hydromorphic soil) during the *Kharif* and *Rabi* seasons of 1992-93 with 4 levels each of ammonium sulphate and ammonium phosphate sulphate (viz. 10, 20, 30 and 40 kg S ha^{-1}) and one control (with no sulphur application). The results of field experiments are presented under the titles biometric observations, yield of rice crop, yield attibutory observations, pest incidence ratings, plant nutrient contents and their removal by rice protein content, plant growth-soil nutrient relationship, studies, economics of sulphur nutrition, and residual effect of sulphur nutrition. Though main effects of source and levels were significant in most of the observations made, interactions between source and level were not significant in most characters. Mention is made on interaction where ever it was significant.

4.3.1 Biometric observations

4.3.1.1 Height of plants

The height of plants at maturity is presented in Table 22. In alluvial soil the height of plants was significantly influenced by sulphur levels in both the seasons. In *Kharif* and *Rabi*, APS increased height of plants over that by AS. In *Kharif* the increase due to levels over control was significant in S_{20}, S_{30} and S_{40} with the maximum at S_{30}. During *Rabi* season the increases due to levels were significant in all levels of sulphur application over control. The maximum height was observed in S_{30}, eventhough S_{20}, S_{30} and S_{40} were on par.

In brown hydromorphic soil during *Kharif* season AS and APS were on par, however, but in *Rabi* APS increased height over that by AS.

In brown hydromorphic soil there was progressive increase in height due to levels of sulphur. During both the seasons S application increased height. In *Kharif* there was progressive increase up to S_{40} but in *Rabi* the maximum increase was upto S_{30} only. In *Kharif* all the levels of S viz., S_{10}, S_{20}, S_{30} and S_{40} were on par and significantly superior to control (S_0). In *Rabi* both S_{30} and S_{40} significantly increased height of plants over control and S_{10}. In general the table shows that sulphur application had increased the height of rice plants.

4.3.1.2 Leaf area index

The leaf area index at 30 DAT, 60 DAT and harvest recorded in the *Kharif* season from experiments in alluvial and brown hydromorphic soils are presented in Table 23.

Table 22. Height of plants at maturity (cm)

Treatments		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of sulphur	AS	73.23	60.62	80.27	67.50
	APS	79.93	62.90	81.07	68.62
LSD at 5%		3.39	0.69	NS	1.08
SEm±		1.14	0.23	0.69	0.36
Control	S_0	69.60	58.47	75.73	64.60
Levels of Sulphur (kg ha^{-1})	S_{10}	72.87	60.57	79.10	66.63
	S_{20}	75.80	61.92	80.77	68.03
	S_{30}	79.93	62.45	81.33	69.13
	S_{40}	77.73	62.10	81.47	68.43
LSD at 5%§		5.88	1.20	3.09	1.87
LSD at 5%§§		4.80	0.98	2.53	1.53
SEm±		1.61	0.33	0.85	0.51
Control	S_0	69.60	58.47	75.73	64.60
Source-1 (A.S)	S_{10}	70.53	59.43	80.13	66.33
	S_{20}	72.67	60.70	80.73	68.00
	S_{30}	76.73	60.77	80.20	67.87
	S_{40}	73.00	61.57	80.00	67.80
Source-2 (APS)	S_{10}	75.20	61.70	78.07	66.93
	S_{20}	78.93	63.13	80.80	68.07
	S_{30}	83.13	64.13	82.47	70.40
	S_{40}	82.47	62.63	82.93	69.07
LSD at 5%		6.79	1.39	3.57	2.15
SEm±		2.27	0.46	1.19	0.71

§ - Between S_0 and levels of S; §§ - Between levels of S

Table 23. Leaf Area Index (*Kharif* season)

Treatments		Alluvial			Brown hydromorphic soil		
		30 DAT	60 DAT	Harvest	30 DAT	60 DAT	Harvest
Source of Sulphur	AS	3.23	4.81	3.09	3.64	4.95	3.49
	APS	3.33	4.92	3.16	3.78	4.99	3.57
LSD at 5%		NS	0.098	NS	NS	NS	NS
SEm±		0.06	0.03	0.02	0.04	0.03	0.02
Levels of Sulphur ($kg\ ha^{-1}$)	S_0	2.59	3.64	2.69	2.73	4.17	2.84
	S_{10}	2.83	4.55	2.98	3.34	4.70	3.19
	S_{20}	3.09	4.88	3.13	3.77	4.96	3.46
	S_{30}	3.48	5.00	3.19	3.88	5.12	3.71
	S_{40}	3.73	5.03	3.21	3.86	5.09	3.77
LSD at 5%§		0.25	0.17	0.11	0.32	0.22	0.10
LSD at 5%		0.21	0.14	0.09	0.26	0.18	0.09
SEm±		0.07	0.05	0.03	0.09	0.06	0.03
Control	S_0	2.59	3.64	2.69	2.73	4.17	2.84
Source-1 (AS)	S_{10}	2.82	4.44	2.95	3.14	4.71	3.16
	S_{20}	3.04	4.85	3.08	3.73	4.90	3.41
	S_{30}	3.45	4.92	3.14	3.85	5.12	3.68
	S_{40}	3.62	5.01	3.19	3.83	5.06	3.73
Source-2 (APS)	S_{10}	2.84	4.65	3.01	3.54	4.69	3.23
	S_{20}	3.14	4.90	3.17	3.80	5.02	3.51
	S_{30}	3.50	5.08	3.24	3.90	5.11	3.74
	S_{40}	3.84	5.05	3.23	3.89	5.12	3.81
LSD at 5%		0.37	0.25	0.12	0.29	0.20	0.12
SEm±		0.12	0.08	0.04	0.10	0.07	0.04

§ - Between S_0 and levels of S; §§ - Between levels of S

Except in alluvial soil at 60 DAT, the LAI was on par in alluvial and brown hydromorphic soils due to the source of sulphur as AS or APS.

The sulphur application increased the leaf area index in both soils during all the three stages. In alluvial soil the increase was progressive upto S_{40} in all stages and the levels S_{30} and S_{40} were on par. In brown hydromorphic soil the progressive increase upto S_{40} is seen only at harvest stage and at 30 DAT and 60 DAT the maximum LAI is seen upto S_{30}. In general the leaf area index has been increased by sulphur application.

4.3.1.3 Number of tillers per hill at maturity

The number of total tillers per hill at maturity of both the soil types of *Kharif* and *Rabi* season are presented in Table 24. In alluvial soil in *Kharif* season APS produced more tillers, but in *Rabi* both AS and AS showed no significant difference in this parameter. The sulphur levels increased tiller production in both seasons. In *Kharif* the highest tiller production was seen upto S_{30}, but the increase was maximum upto S_{20} in *Rabi*. In brown hydromorphic soil there was significantly higher production of tillers by APS over that by As in *Kharif*. However, tiller production by the two sources is on par during *Rabi*. There is progressive increase in tiller production upto S_{30} level during *Kharif* and S_{30} produced 63 per cent more tillers than control plot (S_0). All the sulphur levels significantly increased tiller production than control. During *Rabi* all the higher levels S_{20}, S_{30} and S_{40} kg ha^{-1} showed higher tiller production but the maximum was seen at S_{20}.

Table 24. Number of tillers per hill at maturity

Treatments		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	12.46	12.35	11.62	12.53
	APS	13.55	12.13	13.53	12.72
LSD at 5%		0.58	NS	1.30	NS
SEm±		0.19	0.17	0.43	0.24
Control	S_0	11.40	11.10	9.07	11.40
Level of Sulphur (kg ha^{-1})	S_{10}	12.53	12.17	10.97	12.10
	S_{20}	12.93	12.87	12.80	13.06
	S_{30}	13.33	12.20	14.83	12.82
	S_{40}	13.22	11.70	11.70	12.52
LSD at 5%§		1.00	0.85	2.24	1.22
LSD at 5%§§		0.82	0.69	1.84	0.10
SEm±		0.27	0.23	0.61	0.33
Control	S_0	11.40	11.10	9.07	11.40
Source-1 (AS)	S_{10}	12.10	12.00	10.20	12.40
	S_{20}	12.33	13.10	11.80	12.80
	S_{30}	12.37	12.47	14.20	12.60
	S_{40}	13.03	11.87	10.27	12.33
Source-2 (APS)	S_{10}	12.97	12.33	11.73	11.80
	S_{20}	13.53	12.63	13.80	13.33
	S_{30}	14.30	11.93	15.47	13.03
	S_{40}	13.40	11.53	13.13	12.70
LSD at 5%		1.16	1.03	2.60	1.41
SEm±		0.39	0.35	0.87	0.47

§ - Between S_0 and levels of S; §§ - Between levels of S

4.3.2 Yield of rice crop

4.3.2.1 Grain yield

Yield of grain in kg ha^{-1} from both locations and both seasons of experimentation are presented in Table 25. The mean table shows that APS did significantly increase the rice yield in both locations and in both seasons. The levels of sulphur significantly influenced the yield by increasing it in response to higher S levels. In alluvial soil though sulphur application significantly increased grain yield over control in both seasons, in *kharif* the increase was maximum at S_{20} where as in *Rabi* the maximum yield was recorded at S_{30}. In *Kharif* both S_{20} and S_{30} were on par and significantly superior to other levels including S_{40} which indicates that there was decline in yield when sulphur level was increased. The same phenomenon of yield decline by increase dose from S_{30} to S_{40} was seen during *Rabi* season also in the alluvial soil. In *Rabi*, S_{30} was significantly superior to other levels in production of rice. In brown hydromorphic soil during both season yield increased upto S_{30} and thereafter the yield declined. In general all the levels of sulphur application significantly increased grain yield than control, though, there was decline at the highest level.

4.3.2.2 Yield of straw

The straw yield of both the locations and both the seasons are presented in Table 26. It was seen that source of S had no significant difference in straw yield in all the 4 crops studied. However, the level of sulphur significantly increased straw yield in *Kharif* and *Rabi* at both the locations. In alluvial soil during *Kharif* the straw yield increased significantly at S_{30} and S_{40} over S_0 and S_{10} and all the three levels

Table 25. Yield of grain (kg ha^{-1})

Treatments		Alluvial soils		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	4389.6	4116.7	4400.0	3783.3
	APS	4566.7	4358.3	4541.7	3950.0
LSD at 5%		133.1	91.6	134.2	73.7
SEm±		44.4	30.6	44.8	24.6
Control	S_0	4008.3	3700.0	4008.3	3383.3
Levels of Sulphur (kg ha^{-1})	S_{10}	4312.5	4016.7	4291.7	3658.3
	S_{20}	4608.3	4266.7	4508.3	3908.3
	S_{30}	4591.7	4433.3	4616.7	4033.3
	S_{40}	4400.0	4233.3	4466.7	3866.7
LSD at 5%§		282.2	158.7	232.4	127.6
LSD at 5%§§		188.3	129.6	189.8	104.2
SEm±		62.8	43.2	63.3	34.8
Control	S_0	4008.3	3700.0	4008.3	3383.3
Source-1 (AS)	S_{10}	4241.7	3883.3	4166.7	3600.0
	S_{20}	4433.3	4166.7	4433.3	3866.7
	S_{30}	4566.7	4266.7	4583.3	3900.0
	S_{40}	4316.7	4150.0	4416.7	3766.7
Source-2 (APS)	S_{10}	4383.3	4150.0	4416.7	3717.7
	S_{20}	4783.3	4366.7	4583.3	3950.0
	S_{30}	4616.7	4600.0	4650.0	4166.7
	S_{40}	4483.3	4316.7	4516.7	3966.7
LSD at 5%		266.0	183.3	268.4	147.3
SEm±		88.8	61.1	89.5	49.1

§ - Between S_0 and levels of S; §§ - Between levels of S

Table 26. Yield of straw (kg ha^{-1})

Treatments		Alluvial soil *Kharif*	Alluvial soil *Rabi*	Brown hydromorphic soil *Kharif*	Brown hydromorphic soil *Rabi*
Source of Sulphur	AS	5558.3	5791.7	5645.8	5383.3
	APS	5591.7	6150.0	5658.3	5383.3
LSD at 5%		NS	NS	NS	NS
SEm±		94.0	215.4	63.6	134.4
Control	S_0	4583.3	4683.3	4533.3	4650.0
Levels of Sulphur (kg ha^{-1})	S_{10}	5245.8	5750.0	5366.7	5116.7
	S_{20}	5595.8	6116.7	5666.7	5483.3
	S_{30}	5791.7	6083.3	5941.7	5591.7
	S_{40}	5666.7	5933.3	5633.3	5341.7
LSD at 5%§		487.9	1118.5	330.3	697.7
LSD at 5%		398.4	913.3	269.7	569.7
SEm±		132.9	304.6	81.0	190.0
Control	S_0	4583.3	4683.3	4533.3	4650.0
Source-1 (AS)	S_{10}	5158.3	5600.0	5500.0	5216.7
	S_{20}	5533.3	6233.3	5733.3	5350.0
	S_{30}	5708.3	5633.3	5816.7	5433.3
	S_{40}	5833.3	5700.0	5533.3	5533.3
Source-2 (APS)	S_{10}	5333.3	5900.0	5233.3	5016.7
	S_{20}	5658.3	6000.0	5600.0	5616.7
	S_{30}	5875.0	6533.3	6066.7	5750.0
	S_{40}	5560.0	6166.7	5733.3	5150.0
LSD at 5%		563.4	1291.6	381.4	805.7
SEm±		187.9	430.8	127.2	268.7

§ - Between S_0 and levels of S; §§ - Between levels of S

S_{20}, S_{30} and S_{40} were seen on par with each other. In *Rabi* all the levels of sulphur nutrition were seen significantly superior to control in straw yield and were on par among themselves. Significant interaction of source and sulphur was found during *Kharif* season in alluvial soil where the straw yield was the highest at S_{40} for AS where as it was significantly high at S_{30} for the source APS.

In brown hydromorphic soil the straw yield was found significantly high at S_{30} over other levels in *Kharif* and control (S_0) was significantly poor in straw yield than sulphur applied plots. However in *Rabi* all the levels of sulphur were on par and S_{20}, S_{30} and S_{40} were significantly superior than control.

4.3.3 Yield attributory observations

4.3.3.1 Number of productive tiller (per m^2)

The number of productive tillers per m^2 is presented in Table 27. In alluvial soil at both seasons APS increased productive tillers than that by AS. However, the increase of this parameter in brown hydromorphic soil was not significant. The panicle production per m^2 increased under all levels of sulphur nutrition in all the 4 crops. In all the 4 crops the tiller production was highest at S_{30} and there after the addition of S decreased number of productive tillers.

4.3.3.2 Number of grain per panicle

The number of grains per earhead is presented in Table 28. The mean table shows that only in *Kharif* season at alluvial soil there was significant difference in grains per panicle due to source where APS had higher grains per panicle and in the other three crops the sources were on par. The sulphur application at all levels increased the number of grain per panicle except in *Rabi* at alluvial soil where S_0

Table 27. Number of productive tillers (per m^2)

Treatment		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	372	319	356	330
	APS	388	328	368	333
LSD at 5%		9	6	NS	NS
SEm±		3	2	4	2
Control	S_0	322	260	296	253
Levels of Sulphur ($kg\ ha^{-1}$)	S_{10}	363	308	336	312
	S_{20}	381	324	359	337
	S_{30}	396	336	391	348
	S_{40}	381	325	361	330
LSD at 5%§		16	10	21	12
LSD at 5%§§		13	8	17	10
SEm±		4	3	6	3
Control	S_0	322	260	296	253
Source-1 (AS)	S_{10}	363	303	331	312
	S_{20}	370	318	355	335
	S_{30}	386	331	381	345
	S_{40}	379	322	357	331
Source-2 (APS)	S_{10}	370	313	341	312
	S_{20}	393	331	364	338
	S_{30}	406	341	401	352
	S_{40}	384	327	365	330
LSD at 5%		19	12	24	14
SEm±		6	4	8	5

§ - Between S_0 and levels S; §§ - Between levels of S

Table 28. Number of grains per ear head

Treatments		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of sulphur	AS	59.17	68.08	70.44	57.91
	APS	63.25	59.33	72.00	59.96
LSD at 5%		2.49	NS	NS	NS
SEm±		0.83	0.84	1.48	0.82
Control	S_0	54.00	55.67	59.75	45.67
Levels of Sulphur ($kg\ ha^{-1}$)	S_{10}	58.33	56.67	70.12	55.00
	S_{20}	62.00	61.33	71.87	58.67
	S_{30}	61.83	60.50	73.37	61.12
	S_{40}	62.67	60.33	70.50	60.33
LSD at 5%§		4.30	4.34	7.70	4.27
LSD at 5%§§		3.51	3.55	6.29	3.49
SEm±		1.17	1.18	2.10	1.16
Control	S_0	54.00	55.67	59.75	45.67
Source-1 (AS)	S_{10}	56.33	57.33	72.99	55.67
	S_{20}	60.00	62.00	69.50	58.67
	S_{30}	58.67	60.67	68.95	59.33
	S_{40}	61.67	60.33	70.50	58.00
Source-2 (APS)	S_{10}	60.33	56.00	67.25	54.33
	S_{20}	64.00	60.67	74.25	58.67
	S_{30}	65.00	60.33	75.99	63.00
	S_{40}	63.67	60.33	70.50	62.67
LSD at 5%		4.97	5.01	8.89	4.93
SEm±		1.66	1.67	2.96	1.64

§ - Between S_0 and levels of S; §§ - Between levels of S

and S_{10} were on par. In alluvial soil the maximum grain per earhead was seen at S_{40} during *Kharif* and in *Rabi* it was at S_{20}. In both the seasons the higher levels (viz. S_{10}, S_{20}, S_{30} and S_{40})were on par. In brown hydromorphic soil sulphur application though significantly increased number of grains per earhead over control the levels were on par during *Kharif* season. However, in *Rabi* S_{30} and S_{40} had significantly higher production of grains.

4.3.3.3 Percentage of mature grains

The mean values of percentage of mature grains (filled grains) are presented in Table 29. Sources of S were seen on par in all the three experiments excepting *Rabi* crop in brown hydromorphic soil in which APS significantly increased percentage of mature grains. In alluvial soil during *Kharif* sulphur levels significantly increased the percentage of mature grains and were on par between their. All the S levels though were significantly superior over control, in *Rabi* season, S_{20} and S_{30} were significantly superior to S_{10} and S_{40}. In brown hydromorphic soil the *Kharif* season crop showed that sulphur nutrition increased percentage of mature grains over control. But the levels of S were not significantly different. On the other hand *Rabi* season data showed that only S_{10} and S_{20} had given higher mean values and S_{30} was on par with and S_{40} which was significantly lower than that of control.

4.3.3.4 Weight of panicles (g)

The data on panicle weight is presented in Table 30. In *Kharif* season at alluvial soil and in *Rabi* season at brown hydromorphic soil APS had a higher mean value in panicle weight. There was progressive increase in panicle weight up to S_{40} in alluvial soil during both the seasons. However the progressive increase was seen

Table 29. Percentage of mature grains

Treatments		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	84.50	85.92	79.58	82.67
	APS	85.25	85.33	79.17	83.83
LSD at 5%		NS	NS	NS	0.54
SEm±		0.61	0.32	0.82	0.18
Levels of Sulphur (kg ha^{-1})	S_0	79.69	82.33	79.67	82.33
	S_{10}	83.38	84.83	81.00	83.17
	S_{20}	85.33	86.67	83.00	84.83
	S_{30}	85.67	86.83	79.67	82.50
	S_{40}	85.17	84.17	73.83	81.50
LSD at 5%§		3.19	1.65	4.28	0.94
LSD at 5%		2.61	1.35	3.49	0.76
SEm±		0.87	0.45	1.17	0.26
Control	S_0	79.67	82.33	79.67	82.33
Source-1 (AS)	S_{10}	82.67	85.33	82.33	81.67
	S_{20}	85.00	87.33	83.00	83.67
	S_{30}	85.67	88.00	78.67	82.00
	S_{40}	84.67	83.00	74.33	81.33
Source-2 (APS)	S_{10}	84.00	84.33	79.67	84.67
	S_{20}	85.67	86.00	83.00	86.00
	S_{30}	85.67	85.67	80.67	83.00
	S_{40}	85.67	85.33	73.33	81.67
LSD at 5%		3.69	1.91	4.94	1.08
SEm±		1.23	0.63	1.65	0.36

§ - Between S_0 and levels of S; §§ - Between levels of S

Table 30. Weight of panicle (g)

Treatment		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	1.276	1.274	1.323	1.234
	APS	1.304	1.254	1.316	1.258
LSD at 5%		0.012	NS	NS	0.012
SEm ±		0.004	0.016	0.005	0.004
Control	S_0	1.238	1.226	1.217	1.140
Levels of Sulphur ($kg\ ha^{-1}$)	S_{10}	1.266	1.228	1.310	1.206
	S_{20}	1.286	1.284	1.317	1.252
	S_{30}	1.290	1.266	1.330	1.270
	S_{40}	1.318	1.276	1.317	1.262
LSD at 5% §		0.022	NS	0.026	0.021
LSD at 5% §§		0.018	NS	0.021	0.017
SEm ±		0.006	0.023	0.007	0.006
Control	S_0	1.238	1.226	1.217	1.140
Source-1 (AS)	S_{10}	1.248	1.254	1.324	1.172
	S_{20}	1.284	1.300	1.324	1.244
	S_{30}	1.282	1.270	1.321	1.272
	S_{40}	1.286	1.272	1.319	1.252
Source-2 (APS)	S_{10}	1.284	1.202	1.297	1.238
	S_{20}	1.288	1.270	1.310	1.258
	S_{30}	1.296	1.266	1.337	1.268
	S_{40}	1.350	1.282	1.316	1.270
LSD at 5%		0.024	NS	0.029	0.024
SEm ±		0.008	0.033	0.010	0.008

§ - Between S_0 and levels of S; §§ - Between levels of S

in brown hydromorphic soil only up to S_{30}. In general there was significant increase in weight of panicle by application of sulphur.

4.3.3.5 1000 grain weight

The 1000 grain weight for both seasons and locations are presented in Table 31. Sources had no significant variation in this yield attributing parameter. The levels of S, except during *Kharif* season at brown hydromorphic soil, were on par. In *Kharif* season the crop at hydromorphic location higher levels of S gave increase in 1000 grain weight over control. However S_{20}, S_{30} and S_{40} were on par.

4.3.3.6 Dry matter production (g per m^2)

The data on dry matter production is given in Table 32. In all the 4 field experiments source of S was seen to be on par. However there was significant difference due to levels in all the four trials. During *Kharif* in alluvial soil all the levels were significantly superior. This was the trend seen in the other three crops also. Sulphur levels significantly and progressively increased drymatter production. In all the four field experiments the highest drymatter production was upto 30 kg S per hectare.

4.3.3.7 Grain : Straw ratio

The mean values on grain : straw ratio is presented in Table 33. The mean values were on par.

4.3.3.8 Harvest index

The mean values of harvest index is presented in Table 34. It was seen

Table 31. Test weight of grain (1000 grain weight in g)

Treatments		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	28.36	26.79	27.39	26.30
	APS	28.81	26.27	27.41	26.70
LSD at 5%		NS	NS	NS	NS
SEm±		0.33	0.38	0.12	0.46
Control	S_0	28.43	25.60	26.23	25.10
Level of Sulphur (kg ha^{-1})	S_{10}	28.90	26.43	26.95	25.62
	S_{20}	28.60	26.95	27.59	26.50
	S_{30}	29.67	26.17	27.51	26.95
	S_{40}	28.17	26.57	27.56	27.12
LSD at 5%§		NS	NS	0.63	NS
LSD at 5%§§		NS	NS	0.52	NS
SEm±		0.47	0.54	0.17	0.65
Control	S_0	28.43	25.60	26.23	25.10
Source-1 (AS)	S_{10}	28.90	26.53	27.25	25.53
	S_{20}	28.87	27.60	27.38	26.83
	S_{30}	28.67	26.77	27.48	26.77
	S_{40}	26.90	26.27	27.48	26.43
Source-2 (APS)	S_{10}	28.90	26.33	26.65	25.70
	S_{20}	28.33	26.33	27.81	26.17
	S_{30}	28.51	25.57	27.55	27.13
	S_{40}	29.43	26.87	27.65	27.80
LSD at 5%		NS	NS	0.74	NS
SEm±		0.66	0.76	0.25	0.93

§ Between S_0 and levels of S; §§ - Between levels of S

Table 32. Drymatter production (g per m^2)

Treatment		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	995	991	1005	917
	APS	1022	1051	1020	935
LSD at 5%		40	NS	NS	NS
SEm±		13	25	11	14
Control	S_0	859	838	842	803
Levels of S ($kg\ ha^{-1}$)	S_{10}	956	978	1017	876
	S_{20}	1021	1038	1053	934
	S_{30}	1048	1052	1056	971
	S_{40}	1010	1016	1010	920
LSD at 5%§		68	129	56	73
LSD at 5%§§		56	106	46	60
SEm±		18	35	15	20
Control	S_0	859	838	842	803
Source-1 (AS)	S_{10}	940	948	966	880
	S_{20}	996	1040	1016	905
	S_{30}	1028	990	1040	952
	S_{40}	1015	986	995	930
Source-2 (APS)	S_{10}	971	1006	965	873
	S_{20}	1045	1036	1018	963
	S_{30}	1068	1113	1072	991
	S_{40}	1005	1048	1025	912
LSD at 5%		79	149	65	85
SEm±		26	49	22	28

§ - Between S_0 and levels of S; §§ - Between levels of S

Table 33. Grain : Straw ratio

Treatment		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	0.80	0.71	0.78	0.70
	APS	0.83	0.71	0.80	0.73
LSD at 5%		NS	NS	NS	NS
SEm ±		0.03	0.02	0.03	0.02
Control	S_0	0.87	0.79	0.89	0.72
Levels of Sulphur (kg ha^{-1})	S_{10}	0.82	0.69	0.80	0.71
	S_{20}	0.82	0.69	0.79	0.72
	S_{30}	0.81	0.72	0.77	0.71
	S_{40}	0.78	0.71	0.79	0.72
LSD at 5%		NS	NS	NS	NS
SEm ±		0.04	0.03	0.04	0.03
Control	S_0	0.87	0.79	0.89	0.72
Source-1 (AS)	S_{10}	0.82	0.69	0.75	0.69
	S_{20}	0.80	0.67	0.77	0.70
	S_{30}	0.79	0.75	0.78	0.69
	S_{40}	0.74	0.72	0.80	0.68
Source-2 (ASP)	S_{10}	0.82	0.70	0.84	0.74
	S_{20}	0.84	0.72	0.82	0.69
	S_{30}	0.81	0.70	0.76	0.72
	S_{40}	0.82	0.70	0.78	0.76
LSD at 5%		NS	NS	NS	NS
SEm ±		0.06	0.04	0.06	0.05

Table 34. Harvest Index (%)

Treatment		Alluvial soils		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	44.16	41.67	43.83	42.33
	APS	44.75	42.50	44.42	42.16
LSD at 5%		NS	NS	NS	NS
SEm±		0.48	0.30	0.51	0.81
Control	S_0	46.67	44.33	47.33	42.33
Levels of Sulphur (kg ha^{-1})	S_{10}	45.33	41.33	44.33	41.33
	S_{20}	45.00	41.50	44.17	42.50
	S_{30}	44.00	43.67	43.83	42.00
	S_{40}	43.50	41.83	44.16	43.17
LSD at 5%§		NS	1.55	NS	NS
LSD at 5%§§		NS	1.27	NS	NS
SEm±		0.67	0.42	0.73	1.15
Control	S_0	46.67	44.33	47.33	42.33
Source-1 (AS)	S_{10}	45.33	41.00	43.00	41.00
	S_{20}	44.67	40.33	43.67	43.67
	S_{30}	44.33	43.00	44.33	42.00
	S_{40}	42.33	42.33	44.33	42.67
Source-2 (APS)	S_{10}	45.33	41.67	45.67	41.67
	S_{20}	45.33	42.67	44.67	41.33
	S_{30}	43.67	44.33	43.33	42.00
	S_{40}	44.67	41.33	44.00	43.67
LSD at 5%		NS	1.8	NS	NS
SEm±		0.96	0.6	1.03	1.62

§ - Between S_0 and levels of S; §§ - Between levels of S

the values were statistically on par except at *Rabi* season in the alluvial soil. In this, the level S_{30} and control were on par and significantly superior to other levels.

4.3.3.9 Sink capacity (g per m^2)

Values on sink capacity (g per m^2) are presented in Table 35. In *Kharif* at alluvial soil APS significantly increased sink capacity. The same result was seen in both seasons at brown hydromorphic soil. In *Rabi* season at alluvial soil the sources were on par. In all the four field experiments levels significantly and progressively increased sink capacity of rice. Increase in sink capacity was maximum at S_{30} and S_{40} showed lower mean values, in both soils.

4.3.3.10 Incidence of pests and green algae (score)

The incidence of gall midge, whorl maggot and green algae were visually appeared to be varying with treatment. These parameters were scored as per standard scoring procedure suggested (Anon., 1980) and presented after $\sqrt{x + 1}$ transformation and statistical analysis in Table 36. Whorl maggot incidence at brown hydromorphic soil did not differ significantly with either sources on levels of sulphur. The incidence gall fly at brown hydromorphic soil seemed to be significantly more under sulphur nutrition at all levels. The presence of green algae significantly decreased with levels of sulphur application.

4.3.4 Plant nutrient content and their removal by rice

4.3.4.1 Content of sulphur in grain (%)

The content of sulphur (%) in grain is presented in Table 37. In these field experiments excepting one at brown hydromorphic soil during *Kharif* APS

Table 35. Sink capacity (g per m^2)

Treatment		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	535	410	549	388
	APS	566	409	588	426
LSD at 5%		9	NS	9	9
SEm±		3	4	3	3
Control	S_0	394	296	371	232
Levels of Sulphur (kg ha^{-1})	S_{10}	493	369	524	318
	S_{20}	541	420	567	418
	S_{30}	631	425	623	460
	S_{40}	538	415	561	432
LSD at 5%§		15	21	15	15
LSD at 5%§§		12	17	12	12
SEm±		4	6	4	4
Control	S_0	394	296	371	232
Source-1 (AS)	S_{10}	472	368	526	287
	S_{20}	512	437	540	422
	S_{30}	656	429	577	438
	S_{40}	502	407	553	405
Source-2 (APS)	S_{10}	515	369	521	349
	S_{20}	570	423	594	414
	S_{30}	606	421	670	481
	S_{40}	574	424	568	459
LSD at 5%		18	24	18	17
SEm±		6	8	6	6

§ - Between S_0 and levels of S; §§ - Between levels of S

Table 36. Incidence of pests (scores after $\sqrt{x+1}$ transformation)

Treatments		Brown hydromorphic (Kharif)		
		Gall fly	Whorl maggot	Green algae
Source of Sulphur	AS	2.333	3.827	1.522
	APS	2.244	3.682	1.369
LSD at 5%		NS	NS	0.144
SEm±		0.073	0.266	0.048
Control	S_0	1.821	3.402	2.152
Levels of Sulphur (kg ha^{-1})	S_{10}	2.141	3.709	1.866
	S_{20}	2.428	3.812	1.573
	S_{30}	2.404	4.071	1.276
	S_{40}	2.181	3.427	1.138
LSD at 5%§		0.379	NS	0.248
LSD at 5%§§		0.310	NS	0.203
SEm±		0.103	0.376	0.067
Control	S_0	1.821	3.402	2.157
Source-1 (AS)	S_{10}	1.989	3.647	1.911
	S_{20}	2.698	4.118	1.626
	S_{30}	2.580	4.272	1.414
	S_{40}	2.068	3.274	1.138
Source-2 (APS)	S_{10}	2.294	3.771	1.821
	S_{20}	2.159	3.506	1.520
	S_{30}	2.228	3.871	1.138
	S_{40}	2.294	3.580	1.000
LSD at 5%		0.439	NS	0.288
SEm±		0.146		0.096

§ - Between S_0 and levels of S; §§ - Between levels of S

significantly increased grain sulphur content over that by AS. The grain sulphur significantly increased due to higher levels of S application. The highest level was in S_{40} applied as APS (0.109 %) in *Kharif* season at alluvial soil.

4.3.4.2 Content of S in straw (%)

Sulphur content (%) in straw is presented in Table 38. Content of S in straw was increased by APS during *Kharif* and *Rabi* season in alluvial soil and during *Kharif* in brown hydromorphic soil. During *Rabi* season in brown hydromorphic soil both the sources were seen to be on par. Sulphur content in straw was significantly increased to over three fold in S_{40} treatment compared to control. So also there was steady and progressive increase of S content in straw by higher levels of sulphur. The widest range in content of sulphur in straw was seen in the mean values *Kharif* crop in alluvial soil in which the S content of S_0 was 0.048 per cent and S_{40} (as APS) was 0.181 per cent.

4.3.4.3 Uptake of sulphur (kg ha^{-1})

The uptake of sulphur is presented in Table 39. It was seen that the source of sulphur had significant influence in S uptake and APS removed more sulphur from soil though the same was significant only in alluvial soil and partially in brown hydromorphic soil (*Kharif* season only). Sulphur levels progressively increased uptake of S. The sulphur removal was about 3 fold of that of control by application 40 kg S ha^{-1} in alluvial soil where the control plot (S_0) and highest dose (S_{40}) removed 4.8 and 14.5 kg S ha respectively.

Table 37. Content of Sulphur in grain (%)

Treatments		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AP	0.090	0.085	0.091	0.092
	APS	0.096	0.094	0.091	0.097
LSD at 5%		0.005	0.008	NS	0.002
SEm±		0.002	0.003	0.002	0.001
Control	S_0	0.066	0.061	0.059	0.075
Levels of Sulphur (kg ha^{-1})	S_{10}	0.079	0.080	0.078	0.087
	S_{20}	0.089	0.087	0.087	0.093
	S_{30}	0.098	0.095	0.095	0.096
	S_{40}	0.106	0.096	0.103	0.098
LSD at 5%§		0.008	0.013	0.008	0.004
LSD at 5%§§		0.007	0.011	0.007	0.003
SEm±		0.002	0.004	0.002	0.001
Control	S_0	0.066	0.061	0.059	0.075
Source-1 (AS)	S_{10}	0.077	0.074	0.075	0.084
	S_{20}	0.084	0.081	0.085	0.091
	S_{30}	0.095	0.092	0.095	0.094
	S_{40}	0.104	0.093	0.108	0.097
Source-2 (APS)	S_{10}	0.081	0.085	0.080	0.090
	S_{20}	0.094	0.094	0.089	0.096
	S_{30}	0.102	0.097	0.096	0.098
	S_{40}	0.109	0.099	0.097	0.099
LSD at 5%		0.010	0.016	0.010	0.004
SEm±		0.005	0.008	0.005	0.001

§ - Between S_0 and levels of S; §§ - Between levels of S

Table 38. Content of Sulphur in straw (%)

Treatments		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	0.136	0.095	0.099	0.105
	APS	0.151	0.111	0.120	0.107
LSD at 5%		0.004	0.008	0.011	NS
SEm±		0.001	0.003	0.003	0.001
Control	S_0	0.048	0.050	0.066	0.067
Levels of Sulphur (kg ha^{-1})	S_{10}	0.111	0.082	0.091	0.093
	S_{20}	0.136	0.100	0.101	0.097
	S_{30}	0.154	0.105	0.118	0.114
	S_{40}	0.174	0.126	0.128	0.121
LSD at 5%§		0.007	0.013	0.018	0.008
LSD at 5%§§		0.006	0.011	0.015	0.007
SEm±		0.002	0.004	0.005	0.002
Control	S_0	0.048	0.050	0.066	0.067
Source-1 (AS)	S_{10}	0.099	0.079	0.089	0.092
	S_{20}	0.130	0.099	0.095	0.097
	S_{30}	0.148	0.094	0.100	0.112
	S_{40}	0.166	0.109	0.112	0.120
Source-2 (APS)	S_{10}	0.123	0.085	0.092	0.093
	S_{20}	0.142	0.102	0.108	0.098
	S_{30}	0.159	0.117	0.136	0.117
	S_{40}	0.181	0.143	0.143	0.122
LSD at 5%		0.008	0.016	0.022	0.009
SEm±		0.002	0.005	0.007	0.003

§- Between S_0 and levels of S; §§ - Between levels of S

Table 39. Uptake of Sulphur (kg ha^{-1})

Treatments		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	11.59	9.07	9.48	9.07
	APS	12.78	10.98	10.92	9.58
LSD at 5%		0.90	0.84	0.57	NS
SEm±		0.30	0.28	0.19	0.21
Control	S_0	4.85	4.84	5.42	5.47
Levels of Sulphur (kg ha^{-1})	S_{10}	9.20	8.03	8.21	7.92
	S_{20}	11.75	9.88	9.62	8.84
	S_{30}	13.28	10.63	11.52	10.26
	S_{40}	14.53	11.56	11.46	10.28
LSD at 5%§		1.56	1.45	0.98	1.08
LSD at 5%§§		1.28	1.19	0.80	0.89
SEm±		0.43	0.40	0.27	0.30
Control	S_0	4.85	4.84	5.42	5.47
Source-1 (AS)	S_{10}	8.38	7.50	8.03	7.85
	S_{20}	11.02	9.50	9.09	8.39
	S_{30}	12.79	9.19	10.36	9.71
	S_{40}	14.18	10.06	10.46	10.31
Source-2 (APS)	S_{10}	10.02	8.55	8.39	8.00
	S_{20}	12.47	10.26	10.45	9.29
	S_{30}	13.77	12.07	12.69	10.80
	S_{40}	14.87	13.05	12.46	10.25
LSD at 5%		1.81	1.68	1.14	1.25
SEm±		0.60	0.56	0.38	0.42

§ - Between S_0 and levels of S; §§ - Between levels of S

4.3.4.4 Content of nitrogen in grain (%)

The sources of sulphur except in *Kharif* at alluvial soil did not significantly influence the nitrogen content in grain (Table 40). In *Kharif* season at alluvial soil APS showed a significant edge of increase over AS in nitrogen content. However, the sulphur application levels significantly influenced the nitrogen content of grain. In all the four field experiments shown in the table it can be seen than N content significantly increased by sulphur application over control. However, the content of N was progressive only up to S_{30}; and S_{40} and S_{20} were on par. The highest content was seen at S_{30} applied as APS. All the four levels of S were on par.

4.3.4.5 Content of nitrogen in straw (%)

The N content of straw is presented in Table 41. It was seen that in *Kharif* season at both locations APS increased N content of straw. With regard to levels all the four field experiment showed significant increases in straw N content by sulphur additions. S_0 recorded as low as 0.71 per cent whereas S_{40} as APS as high as 0.98 per cent. All the four levels of S were on par.

4.3.4.6 Uptake of nitrogen (kg ha^{-1})

It is seen from the mean Table 42 that uptake of nitrogen was significantly increased by the source APS over that by AS in all the three experiments excepting the one at brown hydromorphic soil (*Rabi* season). In all the field experiments S application increased nitrogen uptake upto the level of S_{30}. The level S_{40} was on

Table 40. Content of nitrogen in grain (%)

Treatment		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	1.26	1.21	1.18	1.14
	APS	1.31	1.22	1.20	1.14
LSD at 5%		0.05	NS	NS	NS
SEm±		0.02	0.01	0.01	0.01
Control	S_0	1.09	1.19	1.13	1.07
Levels of Sulphur (kg ha^{-1})	S_{10}	1.19	1.21	1.17	1.12
	S_{20}	1.31	1.21	1.20	1.15
	S_{30}	1.33	1.23	1.22	1.16
	S_{40}	1.31	1.21	1.18	1.15
LSD at 5%§		0.08	0.04	0.08	0.06
LSD at 5%§§		0.07	0.03	0.07	0.05
SEm±		0.02	0.01	0.02	0.02
Control	S_0	1.09	1.19	1.13	1.07
Source-1 (AS)	S_{10}	1.16	1.21	1.16	1.11
	S_{20}	1.30	1.21	1.19	1.14
	S_{30}	1.30	1.23	1.19	1.17
	S_{40}	1.28	1.19	1.18	1.15
Source-2 (APS)	S_{10}	1.23	1.22	1.19	1.13
	S_{20}	1.32	1.22	1.20	1.15
	S_{30}	1.37	1.23	1.24	1.15
	S_{40}	1.34	1.23	1.18	1.14
LSD at 5%		0.10	0.04	0.09	0.06
SEm±		0.03	0.01	0.03	0.02

§ - Between S_0 and levels of S; §§ - Between levels of S

Table 41. Content of nitrogen in straw (%)

Treatment		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	0.90	0.92	0.78	0.80
	APS	0.95	0.94	0.86	0.81
LSD at 5%		0.05	NS	0.04	NS
SEm±		0.02	0.01	0.01	0.01
Control	S_0	0.80	0.82	0.71	0.72
Levels of Sulphur (kg ha^{-1})	S_{10}	0.90	0.91	0.80	0.78
	S_{20}	0.90	0.94	0.83	0.78
	S_{30}	0.93	0.94	0.83	0.84
	S_{40}	0.96	0.94	0.83	0.78
LSD at 5%§		0.08	0.07	0.07	0.07
LSD at 5%§§		0.07	0.06	0.06	0.06
SEm±		0.02	0.02	0.02	0.02
Control	S_0	0.80	0.82	0.71	0.72
Source-1 (AS)	S_{10}	0.89	0.88	0.75	0.78
	S_{20}	0.88	0.94	0.77	0.81
	S_{30}	0.88	0.93	0.80	0.82
	S_{40}	0.94	0.94	0.79	0.79
Source-2 (APS)	S_{10}	0.90	0.94	0.84	0.78
	S_{20}	0.95	0.94	0.88	0.82
	S_{30}	0.97	0.94	0.87	0.86
	S_{40}	0.98	0.94	0.87	0.78
LSD at 5%		0.09	0.09	0.08	0.09
SEm±		0.03	0.03	0.03	0.03

§ - Between S_0 and levels of S; §§ - Between levels of S

Table 42. Uptake of Nitrogen (kg ha^{-1})

Treatment		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	105.51	103.08	95.95	86.19
	APS	112.93	110.98	103.14	88.63
LSD at 5%		5.18	5.46	5.57	NS
SEm±		1.73	1.83	1.86	1.45
Control	S_0	80.35	78.73	77.49	69.68
Levels of Sulphur (kg ha^{-1})	S_{10}	93.52	100.92	93.12	80.87
	S_{20}	111.29	107.91	101.12	89.35
	S_{30}	114.93	116.14	105.63	93.74
	S_{40}	112.04	111.22	99.45	86.16
LSD at 5%§		8.97	9.46	9.63	7.53
LSD at 5%§§		7.33	7.73	7.87	6.15
SEm±		9.44	2.58	2.62	2.05
Control	S_0	84.02	79.66	77.49	69.68
Source-1 (AS)	S_{10}	95.10	96.26	89.58	79.86
	S_{20}	106.32	109.00	96.89	87.40
	S_{30}	107.62	104.84	101.06	90.18
	S_{40}	110.09	102.97	95.82	88.68
Source-2 (APS)	S_{10}	101.90	106.09	96.50	81.11
	S_{20}	116.89	109.67	103.72	91.48
	S_{30}	120.22	117.98	110.52	97.36
	S_{40}	114.55	111.05	103.16	85.38
LSD at 5%		10.37	10.92	11.13	8.70
SEm±		3.46	3.64	3.71	2.90

§ - Between S_0 and levels of S; §§ - Between levels of S

par with S_{20} and S_{30}. Except in *Rabi*, at brown hydromorphic soil, where S_{40} was significantly lower than S_{30}, in all the other 3 crops S_{40} and S_{30} were on par.

4.3.4.7 Content of phosphorus in grain (%)

The phosphorus content in grain is presented in Table 43. The sources of sulphur was not showing any influence and were on par. In both the soils there was significant variation in P content of grain due to sulphur levels. In general there was decrease in P content of grain due to sulphur application. Higher levels further decreased P content. The highest concentration of P was seen in control (no sulphur treatment).

4.3.4.8 Content of phosphorus in straw (%)

Content of P in straw is presented in Table 44. The general trend was that APS had higher content of P in straw except in *Rabi* at alluvial soil. In *Kharif* season at alluvial soil the increase in P content due to APS over that by AS was significant. As in the case of P content of grain there was a general trend of decline in P content of straw due to higher levels of sulphur. The P content was high at control plots; and statistically significant increase in P content in control was seen in comparison with higher levels of sulphur application.

4.3.4.9 Uptake of phosphorus (kg ha^{-1})

The uptake of phosphorus is presented in Table 45. In general APS had increased P uptake which was significant only in *Kharif* season at alluvial soil. Similarly the increase in P uptake reached maximum at S_{20} and declined there after with higher S levels. This trend was statistically significant only at alluvial soil during *Kharif* season.

Table 43. Content of Phosphorus in grain (%)

Treatments		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	0.254	0.248	0.232	0.241
	APS	0.256	0.243	0.224	0.242
LSD at 5%		NS	NS	NS	NS
SEm±		0.003	0.003	0.003	0.003
Control	S_0	0.266	0.270	0.246	0.273
Levels of Sulphur (kg ha^{-1})	S_{10}	0.263	0.258	0.235	0.253
	S_{20}	0.260	0.250	0.237	0.253
	S_{30}	0.253	0.243	0.220	0.237
	S_{40}	0.243	0.230	0.220	0.223
LSD at 5%§		0.015	0.019	0.019	0.018
LSD at 5%§§		0.012	0.016	0.016	0.015
SEm±		0.004	0.005	0.005	0.005
Control	S_0	0.266	0.270	0.246	0.273
Source-1 (AS)	S_{10}	0.263	0.263	0.233	0.263
	S_{20}	0.256	0.250	0.240	0.263
	S_{30}	0.253	0.246	0.226	0.223
	S_{40}	0.243	0.230	0.226	0.213
Source-2 (APS)	S_{10}	0.263	0.253	0.236	0.243
	S_{20}	0.263	0.250	0.233	0.243
	S_{30}	0.253	0.240	0.213	0.250
	S_{40}	0.243	0.230	0.213	0.233
LSD at 5%		0.017	0.022	0.022	0.021
SEm±		0.006	0.007	0.007	0.007

§ - Between S_0 and levels of S; §§ - Between levels of S

Table 44. Content of phosphorus in straw (%)

Treatments		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	0.159	0.150	0.146	0.122
	APS	0.175	0.142	0.147	0.129
LSD at 5%		0.011	NS	NS	NS
SEm±		0.003	0.003	0.003	0.003
Control	S_0	0.180	0.173	0.170	0.153
Levels of Sulphur ($kg\ ha^{-1}$)	S_{10}	0.175	0.162	0.160	0.140
	S_{20}	0.173	0.166	0.153	0.128
	S_{30}	0.167	0.142	0.148	0.117
	S_{40}	0.153	0.120	0.125	0.117
LSD at 5%§		0.018	0.017	0.021	0.017
LSD at 5%§§		0.015	0.014	0.017	0.014
Sem±		0.005	0.004	0.005	0.004
Control	S_0	0.180	0.173	0.170	0.153
Source-1 (AS)	S_{10}	0.170	0.166	0.156	0.143
	S_{20}	0.160	0.160	0.156	0.126
	S_{30}	0.156	0.146	0.146	0.106
	S_{40}	0.150	0.126	0.123	0.110
Source-2 (APS)	S_{10}	0.180	0.156	0.163	0.136
	S_{20}	0.187	0.160	0.150	0.130
	S_{30}	0.176	0.136	0.150	0.126
	S_{40}	0.156	0.113	0.126	0.123
LSD at 5%		0.021	0.019	0.023	0.020
SEm±		0.007	0.006	0.007	0.006

§ - Between S_0 and levels of S; §§ - Between levels of S

Table 45. Uptake of phosphorus (kg ha^{-1})

Treatments		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	19.96	18.87	18.38	16.09
	APS	21.48	19.41	18.61	16.23
LSD at 5%		0.681	NS	NS	NS
SEm±		0.227	0.482	0.438	0.448
Control	S_0	19.12	18.13	17.56	16.39
Levels of Sulphur (kg ha^{-1})	S_{10}	20.55	19.60	18.67	16.59
	S_{20}	21.68	20.43	19.20	16.75
	S_{30}	21.27	19.31	18.96	16.29
	S_{40}	19.38	17.22	17.14	15.01
LSD at 5%§		1.18	NS	NS	NS
LSD at 5%§§		0.96	NS	NS	NS
SEm±		0.32	0.68	0.55	0.63
Control	S_0	19.12	18.13	17.56	16.39
Source-1 (AS)	S_{10}	19.94	19.51	18.32	17.28
	S_{20}	20.22	20.47	19.47	16.56
	S_{30}	20.47	18.77	18.94	15.66
	S_{40}	19.22	16.74	16.83	14.87
Source-2 (APS)	S_{10}	21.16	19.69	19.01	15.90
	S_{20}	23.15	20.40	19.08	16.93
	S_{30}	22.08	19.85	18.98	16.94
	S_{40}	19.54	17.71	17.44	15.15
LSD at 5%		1.36	NS	NS	NS
SEm±		0.45	0.97	0.88	0.90

§ - Between S_0 and levels of S; §§ - Between levels of S

4.3.4.10 Content of potassium in grain (%)

The content of potassium in grain is presented in Table 46. Except at *Rabi* season, in brown hydromorphic soil, in other three field experiments K content in grain significantly increased due to the source APS compared to that by AS. There was progressively higher content of K in grain due to higher levels of sulphur application. The K content steadily increased and the maximum was in S_{40}.

4.3.4.11 Content of potassium in straw (%)

The content of potassium in straw is presented in Table 47. The general trend with regard to source in influencing K content of straw showed that APS significantly increased the K content in straw compared to AS. This was significant in both seasons at brown hydromorphic soils and during *Rabi* season at alluvial soil. There was significant increase in potassium content of straw with higher levels of S. In all four crops it was evident that potassium content was significantly low in control plot. So also the highest concentration was seen at S_{40}.

4.3.4.12 Uptake of potassium (kg ha^{-1})

Uptake of potassium is presented in Table 48. The uptake was high due to the source APS compared to AS. However this trend was significant only in two crops viz. in *Rabi* at alluvial soil and in *Kharif* at brown hydromorphic soil. The uptake of potassium was significantly increased in all the trials and the uptake was less at control plot. The increase was steady and progressive upto S_{30}. The uptake of K in S_{30} and S_{40} were on par.

Table 46. Content of potassium in grain (%)

Treatments		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	0.447	0.356	0.428	0.362
	APS	0.478	0.373	0.450	0.368
LSD at 5%		0.016	0.011	0.015	NS
SEm±		0.005	0.003	0.065	0.003
Control	S_0	0.390	0.336	0.366	0.350
Levels of Sulphur (kg ha^{-1})	S_{10}	0.433	0.353	0.397	0.350
	S_{20}	0.458	0.362	0.428	0.362
	S_{30}	0.472	0.367	0.458	0.372
	S_{40}	0.487	0.377	0.472	0.378
LSD at 5%§		0.029	0.018	0.025	0.021
LSD at 5%§§		0.024	0.015	0.021	0.017
SEm±		0.008	0.005	0.007	0.005
Control	S_0	0.390	0.336	0.366	0.350
Source-1 (AS)	S_{10}	0.406	0.353	0.386	0.346
	S_{20}	0.440	0.353	0.416	0.356
	S_{30}	0.460	0.353	0.440	0.370
	S_{40}	0.480	0.363	0.466	0.376
Source-2 (APS)	S_{10}	0.460	0.353	0.406	0.353
	S_{20}	0.476	0.370	0.440	0.366
	S_{30}	0.483	0.380	0.476	0.373
	S_{40}	0.493	0.393	0.476	0.380
LDS at 5%		0.033	0.021	0.030	0.023
SEm±		0.011	0.007	0.010	0.007

§ - Between S_0 and levels of S; §§ - Between levels of S

Table 47. Content of potassium in straw (%)

Treatments		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	2.87	2.50	2.58	2.79
	APS	2.85	2.61	2.64	2.88
LSD at 5%		NS	0.04	0.05	0.04
SEm±		0.05	0.01	0.02	0.01
Control	S_0	2.44	2.28	2.38	2.54
Levels of Sulphur (kg ha^{-1})	S_{10}	2.80	2.39	2.49	2.73
	S_{20}	2.91	2.52	2.57	2.82
	S_{30}	2.76	2.60	2.62	2.88
	S_{40}	2.96	2.72	2.77	2.92
LSD at 5%§		0.28	0.07	0.09	0.07
LSD at 5%		0.23	0.06	0.07	0.06
SEm±		0.08	0.02	0.02	0.02
Control	S_0	2.44	2.28	2.38	2.54
Source-1 (AS)	S_{10}	2.76	2.37	2.44	2.69
	S_{20}	2.88	2.47	2.54	2.77
	S_{30}	2.90	2.51	2.57	2.83
	S_{40}	2.93	2.66	2.79	2.88
Source-2 (APS)	S_{10}	2.84	2.41	2.55	2.76
	S_{20}	2.94	2.58	2.60	2.88
	S_{30}	2.63	2.69	2.68	2.92
	S_{40}	3.00	2.77	2.75	2.97
LSD at 5%		0.33	0.08	0.10	0.08
SEm±		0.11	0.03	0.03	0.03

§ - Between S_0 and levels of S; §§ - Between levels of S

Table 48. Uptake of potassium (kg ha^{-1})

Treatment		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	180.25	158.42	164.79	162.33
	APS	185.19	177.35	170.37	169.31
LSD at 5%		NS	15.45	4.83	NS
SEm±		3.44	5.15	1.61	4.13
Control	S_0	127.52	119.28	122.5	130.19
Level of Sulphur (kg ha^{-1})	S_{10}	164.18	150.71	150.71	150.88
	S_{20}	185.44	169.94	165.05	164.80
	S_{30}	191.76	175.05	177.33	176.60
	S_{40}	189.53	175.83	177.23	171.02
LSD at 5%§		17.86	26.76	8.36	21.44
LSD at 5%§§		14.58	21.85	6.83	17.51
SEm±		4.86	7.29	2.28	5.84
Control	S_0	127.52	119.28	122.50	130.19
Source-1 (AS)	S_{10}	159.68	144.48	150.04	153.02
	S_{20}	182.39	168.68	164.23	153.19
	S_{30}	186.88	156.85	169.73	169.44
	S_{40}	192.07	163.68	175.17	173.67
Source-2 (APS)	S_{10}	168.67	156.93	151.38	148.73
	S_{20}	188.49	171.21	165.88	176.41
	S_{30}	196.36	193.25	184.93	183.76
	S_{40}	186.99	188.00	179.28	168.36
LSD at 5%		20.62	30.89	9.65	24.75
SEm±		6.88	10.30	3.21	8.25

§ - Between S_0 and levels of S; §§ - Between levels of S

4.3.4.13 Calcium content of grain (%)

The calcium content of grain is presented in Table 49. There was no significant influence seen due to sources. The content of grain was on par during *Rabi* seasons on both the locations. In *Kharif* season at both locations there was significant difference in Ca content of grain by higher levels of sulphur. S_{10} recorded the highest calcium content which was on par upto S_{30} followed by significant decrease by increased S levels.

4.3.4.14 Calcium content of straw (%)

The calcium content of straw is presented in Table 50. The source of sulphur showed influence in calcium content in straw, only in brown hydromorphic soil where AS increased the Ca content in straw. However, in alluvial soil both sources were on par. The sulphur application in general decreased the calcium content in straw. The decrease was significant only at higher levels and S_0 and S_{10} were on par in all the four field experiments. The calcium content of straw was high in brown hydromorphic soils compared to alluvial soil.

4.3.4.15 Uptake of calcium (kg ha^{-1})

The calcium uptake is presented in Table 51. The effect of sulphur sources was on par except at brown hydromorphic soil during *Kharif* season where S uptake significantly increased with AS application. With regard to levels the general trend was increases in calcium uptake at lower levels of sulphur over control which was significant at *Kharif* seasons. In *Rabi* at alluvial both sources were on par and

Table 49. Content calcium of grain (%)

Treatment		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	0.044	0.034	0.040	0.032
	APS	0.046	0.036	0.040	0.033
LSD at 5%		NS	NS	NS	NS
SEm±		0.001	0.001	0.002	0.003
Control	S_0	0.048	0.036	0.045	0.030
Levels of Sulphur (kg ha^{-1})	S_{10}	0.050	0.038	0.045	0.034
	S_{20}	0.047	0.037	0.044	0.038
	S_{30}	0.043	0.035	0.037	0.030
	S_{40}	0.041	0.031	0.035	0.028
LSD at 5%§		0.006	NS	0.007	NS
LSD at 5%§§		0.005	NS	0.006	NS
SEm±		0.002	0.002	0.002	0.004
Control	S_0	0.048	0.036	0.045	0.030
Source-1 (AS)	S_{10}	0.050	0.037	0.046	0.033
	S_{20}	0.046	0.035	0.044	0.041
	S_{30}	0.042	0.035	0.036	0.029
	S_{40}	0.040	0.030	0.034	0.026
Source-2 (APS)	S_{10}	0.050	0.039	0.044	0.034
	S_{20}	0.047	0.038	0.044	0.035
	S_{30}	0.043	0.036	0.037	0.031
	S_{40}	0.042	0.033	0.036	0.030
LSD at 5%		0.007	NS	0.009	NS
SEm±		0.002	0.003	0.003	0.006

§ - Between S_0 and levels of S; §§ - Between levels of S

Table 50. Content of calcium in straw (%)

Treatment		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	0.431	0.387	0.655	0.664
	APS	0.427	0.386	0.589	0.587
LSD at 5%		NS	NS	0.047	0.027
SEm±		0.006	0.006	0.015	0.009
Control	S_0	0.513	0.424	0.746	0.722
Level of Sulphur ($kg\ ha^{-1}$)	S_{10}	0.497	0.423	0.722	0.692
	S_{20}	0.475	0.388	0.661	0.676
	S_{30}	0.378	0.368	0.578	0.601
	S_{40}	0.366	0.367	0.528	0.532
LSD at 5%§		0.033	0.030	0.082	0.046
LSD at 5%§§		0.027	0.025	0.067	0.038
SEm±		0.009	0.008	0.022	0.013
Control	S_0	0.513	0.424	0.746	0.721
Source-1 (AS)	S_{10}	0.498	0.422	0.771	0.721
	S_{20}	0.476	0.387	0.708	0.721
	S_{30}	0.385	0.371	0.597	0.654
	S_{40}	0.367	0.369	0.544	0.561
Source-2 (APS)	S_{10}	0.497	0.425	0.673	0.663
	S_{20}	0.475	0.390	0.615	0.631
	S_{30}	0.372	0.365	0.553	0.549
	S_{40}	0.364	0.365	0.512	0.504
LDS at 5%		0.038	0.035	0.095	0.054
SEm±		0.013	0.012	0.032	0.018

§ - Between S_0 and levels S; §§ - Between levels of S

Table 51. Uptake of calcium (kg ha^{-1})

Treatment		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	25.89	22.85	38.62	36.28
	APS	25.86	24.77	34.94	32.97
LSD at 5%		NS	NS	2.32	NS
SEm±		0.35	1.23	0.77	1.18
Control	S_0	25.45	21.25	35.29	34.57
Levels of Sulphur (kg ha^{-1})	S_{10}	28.25	25.41	40.68	36.67
	S_{20}	28.83	24.55	39.38	37.34
	S_{30}	23.90	23.12	35.78	34.97
	S_{40}	22.51	22.16	31.28	29.51
LSD at 5%§		1.80	NS	4.02	6.08
LSD at 5%§§		1.47	NS	3.28	4.97
SEm±		0.49	1.74	1.09	1.66
Control	S_0	25.45	21.25	35.29	34.57
Source-1 (AS)	S_{10}	27.77	25.00	44.23	38.84
	S_{20}	28.69	25.52	42.40	37.29
	S_{30}	23.92	21.61	36.27	37.07
	S_{40}	23.15	19.26	31.60	31.98
Source-2 (APS)	S_{10}	28.73	25.81	37.01	34.58
	S_{20}	28.96	23.57	36.35	37.39
	S_{30}	23.88	24.63	35.33	32.87
	S_{40}	21.87	25.06	30.96	27.03
LSD at 5%		2.08	NS	4.64	7.04
SEm±		0.69	2.46	1.55	2.35

§ - Between S_0 and levels of S; §§ - Between levels of S

similarly in brown hydromorphic the sources were not significant. The decreases in calcium uptake were significant between control and S_{40} except in alluvial (*Rabi*).

4.3.4.16 Magnesium content of grain (%)

Magnesium content of grain is presented in Table 52. It was seen that in general the content of magnesium was more in rice grown in brown hydromorphic soils. The sources did not vary except at brown hydromorphic soil during *Kharif* season where significantly higher content was in AS applied plots compared to APS. The content of Mg increased in general with levels of sulphur application but the higher levels of sulphur decreased the Mg content of grain.

4.3.4.17 Magnesium content of straw (%)

The magnesium content of straw is presented in Table 53. In general APS increased in Mg content which was significant in 3 field trials except at *Kharif* season in alluvial soil. The general trend on the effect of levels of sulphur shows Mg content was increased in straw upto S_{20} over control which was significant in alluvial soil (*Rabi*) and brown hydromorphic (*Kharif*) crop. However there were decreases in Mg content in straw when S levels increased to 40 kg S ha^{-1}.

4.3.4.18 Magnesium uptake (kg ha^{-1})

The magnesium uptake is presented in Table 54. In general the magnesium uptake increased by APS over that by AS which was significant in the three field trials except *Kharif* season crop in brown hydromorphic soil. There was steady and progressive increase in Mg uptake by levels of sulphur upto S_{20} which there after decreased. In *Rabi* at brown hydromorphic soil the highest uptake was seen at S_{30}.

Table 52. Content of magnesium in grain (%)

Treatment		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	0.121	0.123	0.139	0.125
	APS	0.123	0.122	0.130	0.127
LSD at 5%		NS	NS	0.004	NS
SEm±		0.001	0.009	0.001	0.001
Control	S_0	0.115	0.123	0.138	0.128
Level of Sulphur (kg ha^{-1})	S_{10}	0.127	0.126	0.143	0.131
	S_{20}	0.123	0.114	0.143	0.131
	S_{30}	0.120	0.133	0.132	0.122
	S_{40}	0.117	0.116	0.121	0.121
LSD at 5%§		0.006	NS	0.006	0.006
LSD at 5%§§		0.005	NS	0.005	0.005
SEm±		0.002	0.012	0.002	0.002
Control	S_0	0.115	0.123	0.138	0.128
Source-1 (AS)	S_{10}	0.124	0.126	0.142	0.130
	S_{20}	0.121	0.130	0.145	0.130
	S_{30}	0.120	0.119	0.143	0.121
	S_{40}	0.118	0.116	0.127	0.120
Source-2 (APS)	S_{10}	0.130	0.126	0.143	0.132
	S_{20}	0.126	0.098	0.142	0.131
	S_{30}	0.119	0.147	0.121	0.124
	S_{40}	0.117	0.115	0.114	0.122
LSD at 5%		0.008	NS	0.007	0.007
SEm±		0.003	0.018	0.002	0.002

§ - Between S_0 and level of S; §§ - Between levels of S

Table 53. Content of magnesium in straw (%)

Treatment		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	0.145	0.119	0.122	0.155
	APS	0.151	0.126	0.131	0.160
LSD at 5%		NS	0.005	0.004	0.002
SEm±		0.005	0.002	0.001	0.001
Control	S_0	0.162	0.117	0.115	0.165
Level of Sulphur ($kg\ ha^{-1}$)	S_{10}	0.161	0.129	0.132	0.169
	S_{20}	0.160	0.127	0.130	0.162
	S_{30}	0.140	0.118	0.125	0.159
	S_{40}	0.130	0.117	0.120	0.140
LSD at 5%§		0.025	0.008	0.006	0.004
LSD at 5%§§		0.021	0.007	0.005	0.003
SEm±		0.007	0.002	0.002	0.001
Control	S_0	0.162	0.117	0.115	0.165
Source-1 (AS)	S_{10}	0.158	0.124	0.125	0.166
	S_{20}	0.153	0.122	0.124	0.161
	S_{30}	0.139	0.115	0.123	0.155
	S_{40}	0.129	0.115	0.116	0.138
Source-2 (APS)	S_{10}	0.165	0.133	0.138	0.171
	S_{20}	0.168	0.131	0.136	0.163
	S_{30}	0.141	0.122	0.127	0.164
	S_{40}	0.131	0.119	0.125	0.142
LSD at 5%		0.029	0.010	0.008	0.004
SEm±		0.010	0.003	0.003	0.001

§ - Between S_0 and levels of S; §§ - Between levels of S

Table 54. Uptake of magnesium (kg ha^{-1})

Treatment		Alluvial soils		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	13.42	11.92	13.02	12.78
	APS	13.99	13.38	13.34	13.64
LSD at 5%		0.47	0.85	NS	0.85
SEm±		0.15	0.28	0.14	0.28
Control	S_0	12.04	10.05	10.75	12.35
Levels of Sulphur (kg ha^{-1})	S_{10}	13.94	12.41	13.18	13.05
	S_{20}	14.53	13.29	13.85	13.73
	S_{30}	13.81	13.09	13.51	13.86
	S_{40}	12.53	11.81	12.18	12.16
LSD at 5%§		0.81	1.48	0.73	1.46
LSD at 5%§§		0.66	1.21	0.60	1.20
SEm±		0.22	0.40	0.20	0.40
Control	S_0	12.04	10.05	10.75	12.35
Source-1 (AS)	S_{10}	13.39	11.87	12.79	12.67
	S_{20}	13.83	13.05	13.53	13.13
	S_{30}	13.83	11.50	13.71	13.14
	S_{40}	12.63	11.25	12.04	12.17
Source-2 (APS)	S_{10}	14.49	12.93	13.56	13.49
	S_{20}	15.23	13.53	14.19	14.33
	S_{30}	13.79	14.70	13.30	14.59
	S_{40}	12.42	12.36	12.31	12.15
LSD at 5%		0.94	1.72	0.85	1.70
SEm±		0.32	0.57	0.28	0.57

§ - Between S_0 and levels of S; §§ - Between levels of S

4.3.4.19 Zinc content in grain (ppm)

The zinc content in grain is presented in Table 55. The sources of sulphur were on par at all the four trials. The low levels of sulphur generally increased the zinc content in grain and the highest content was in S_{10}. However, the increased doses of sulphur drastically reduced the zinc content in grain which was significant at S_{40}. The zinc content in grain was generally low at brown hydromorphic soils (24.9 ppm) compared to alluvial (43.8 ppm).

4.3.4.20 Zinc content of straw (ppm)

Zinc content of straw is presented in Table 56. The sources were on par in zinc content of straw except at *Rabi* season in brown hydromorphic soil where a higher content was noticed by the source APS. The levels of S showed that the zinc content in straw in control plot was high in *Kharif* season at alluvial soil. However, in *Rabi* crop (alluvial) and *Kharif* crop (brown hydromorphic) significantly higher content of zinc was observed at S_{10} over S_0 (control). In general, the higher levels of sulphur (S_{30} and S_{40}) recorded the lowest zinc contents in straw which were significant compared to control.

4.3.4.21 Uptake of Zinc (kg ha^{-1})

The uptake of zinc is presented in Table 57. APS in general increased the uptake of zinc by rice which was statistically significant in alluvial (*Kharif*) and brown hydromorphic soil (*Rabi*). There was increase in zinc uptake at lower levels of sulphur. The zinc uptake decreased beyond S_{20} in all the four field trials and S_{40} recorded the lowest. The uptake by rice in alluvial soils were high compared to that in brown hydromorphic soil and were approximately about double in values.

Table 55. Content of zinc in grain (ppm)

Treatment		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Khari*	*Rabi*
Source of Sulphur	AS	43.0	43.3	25.8	25.2
	APS	42.7	44.4	26.1	24.6
LSD at 5%		NS	NS	NS	NS
SEm±		0.5	0.4	0.3	0.3
Control	S_0	42.7	44.0	28.6	28.0
Levels of Sulphur (kg ha^{-1})	S_{10}	45.2	46.8	28.8	27.5
	S_{20}	45.2	45.7	28.2	26.2
	S_{30}	42.0	42.8	28.8	23.3
	S_{40}	39.0	40.2	22.8	22.5
LSD at 5%§		2.3	2.3	1.7	1.5
LSD at 5%§§		1.9	1.9	1.4	1.2
SEm±		0.6	0.6	0.5	0.4
Control	S_0	42.7	44.0	28.6	28.0
Source-1 (AS)	S_{10}	43.3	45.7	29.3	27.7
	S_{20}	43.6	45.0	28.3	25.7
	S_{30}	44.3	43.0	23.0	24.0
	S_{40}	40.7	39.7	22.3	23.3
Source-2 (APS)	S_{10}	47.0	48.0	28.3	27.3
	S_{20}	46.7	46.3	28.0	26.7
	S_{30}	39.7	42.7	24.7	22.7
	S_{40}	37.3	40.7	23.3	21.7
LSD at 5%		2.7	2.7	1.9	1.8
SEm±		0.9	0.9	0.6	0.6

§ - Between S_0 and levels of S; §§ - Between levels of S

Table 56. Content of zinc in straw (ppm)

Treatment		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	74.2	71.3	31.5	31.4
	APS	74.5	70.3	30.8	33.6
LSD at 5%		NS	NS	NS	1.4
SEm±		0.9	0.7	1.0	0.5
Control	S_0	94.7	78.3	31.6	37.0
Level of Sulphur (kg ha^{-1})	S_{10}	76.5	85.2	37.2	37.3
	S_{20}	80.2	74.2	37.5	33.0
	S_{30}	71.2	65.3	27.0	31.0
	S_{40}	69.3	58.5	23.0	28.7
LSD at 5%§		4.8	3.6	5.5	2.5
LSD at 5%§§		3.9	2.9	4.5	2.0
SEm±		1.3	1.0	1.5	0.7
Control	S_0	94.7	78.3	31.6	37.0
Source-1 (AS)	S_{10}	87.0	86.3	36.0	38.0
	S_{20}	73.6	75.3	38.3	31.6
	S_{30}	68.3	65.7	29.0	29.7
	S_{40}	67.7	57.7	22.7	26.3
Source-2 (APS)	S_{10}	66.0	84.0	38.3	36.4
	S_{20}	86.7	73.0	36.7	34.3
	S_{30}	74.0	65.0	25.0	32.3
	S_{40}	71.0	59.3	23.3	31.0
LSD at 5%		5.6	4.1	6.3	2.9
SEm±		1.9	1.4	2.1	1.0

§ - Between S_0 and levels of S; §§ - Between levels of S

Table 57. Uptake of zinc (kg ha^{-1})

Treatment		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	0.597	0.585	0.291	0.260
	APS	0.631	0.619	0.292	0.277
LSD at 5%		0.022	NS	NS	0.012
SEm±		0.007	0.016	0.009	0.003
Control	S_0	0.607	0.527	0.258	0.266
Levels of Sulphur (kg ha^{-1})	S_{10}	0.645	0.661	0.327	0.291
	S_{20}	0.651	0.650	0.341	0.277
	S_{30}	0.605	0.578	0.267	0.266
	S_{40}	0.556	0.520	0.231	0.239
LSD at 5%§		0.039	0.083	0.044	0.021
LSD at 5%§§		0.032	0.068	0.036	0.017
SEm±		0.011	0.023	0.012	0.006
Control	S_0	0.607	0.527	0.258	0.266
Source-1 (AS)	S_{10}	0.637	0.630	0.321	0.298
	S_{20}	0.600	0.660	0.350	0.257
	S_{30}	0.593	0.553	0.270	0.253
	S_{40}	0.560	0.497	0.224	0.234
Source-2 (APS)	S_{10}	0.653	0.693	0.334	0.285
	S_{20}	0.703	0.640	0.333	0.298
	S_{30}	0.617	0.603	0.265	0.280
	S_{40}	0.553	0.543	0.238	0.245
LSD at 5%		0.045	0.096	0.052	0.024
SEm±		0.015	0.032	0.017	0.008

§ - Between S_0 and levels of S; §§ - Between levels of S

4.3.4.22 Manganese content of grain (ppm)

The manganese content of grain is presented in Table 58. In all the field trials the content of manganese was on par with regard to sources of sulphur. In the case of levels S_0 recorded highest content in two trials and S_{10} and S_{30} in other two trials. However, it was significantly clear that the highest levels S (S_{40}) decreased the manganese content of grain.

4.3.4.23 Manganese content of straw (ppm)

The manganese content of straw is presented in Table 59. It is seen that sources of S levels were on par except in *Kharif* season at brown hydromorphic soil where AS increased the Mn content in straw. The content of Mn in straw generally was high towards low levels and except in *Rabi* at brown hydromorphic soil in other three trials the highest mean values were seen for control plot crop. There was high variation in Mn content with respect to location. Rice plant from brown hydromorphic soil contained more Mn compared to that in alluvial soil and was almost double in most cases.

4.3.4.24 Uptake of Manganese (kg ha^{-1})

Uptake of manganese by rice crop in 4 trials are presented in Table 60. It was seen that the sources were on par. With regard to effect of sulphur doses the 4 trials showed differentially and significantly. In general the trend was diminishing level of manganese uptake with increase in sulphur dose and the highest level of sulphur (S_{40}) recorded the least uptake of Mn than lower levels. This decrease was significant and seen in all the four trials.

Table 58. Content of manganese in grain (ppm)

Treatment		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	85.6	71.5	146.1	160.7
	APS	83.6	79.0	142.8	152.5
LSD at 5%		NS	NS	NS	NS
SEm±		1.4	2.9	2.5	3.3
Control	S_0	99.0	78.0	138.0	213.3
Levels of Sulphur ($kg\ ha^{-1}$)	S_{10}	98.7	85.2	144.7	187.2
	S_{20}	87.3	79.3	146.3	166.0
	S_{30}	81.5	70.7	152.3	146.3
	S_{40}	70.8	65.8	134.5	127.0
LSD at 5%§		7.4	14.9	12.3	16.9
LSD at 5%§§		6.0	12.2	10.1	13.8
SEm±		2.0	4.1	3.6	4.6
Control	S_0	99.0	78.0	138.0	213.3
Source-1 (AS)	S_{10}	102.3	80.7	138.7	193.3
	S_{20}	84.7	79.0	141.7	177.6
	S_{30}	81.3	65.0	166.0	145.0
	S_{40}	74.0	61.3	138.0	127.0
Source-2 (APS)	S_{10}	95.0	89.7	150.7	181.0
	S_{20}	90.0	79.7	151.0	154.3
	S_{30}	81.7	76.3	138.7	147.7
	S_{40}	67.7	70.3	131.0	127.0
LSD at 5%		8.5	17.3	15.1	19.6
SEm±		2.8	5.8	5.0	6.5

§ - Between S_0 and levels of S; §§ - Between levels of S

Table 59. Content of manganese in straw (ppm)

Treatment		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	944	851	1533	1652
	APS	920	853	1435	1616
LSD at 5%		NS	NS	48	NS
SEm±		10	6	16	20
Control	S_0	1033	983	2073	1765
Level of Sulphur (kg ha^{-1})	S_{10}	1071	940	1773	1829
	S_{20}	1005	893	1593	1721
	S_{30}	899	841	1392	1557
	S_{40}	755	733	1177	1428
LSD at 5%§		56	34	83	104
LSD at 5%§§		46	28	67	85
SEm±		15	9	22	28
Control	S_0	1083	983	2073	1765
Source-1 (AS)	S_{10}	1082	963	1860	1850
	S_{20}	984	895	1656	1716
	S_{30}	913	866	1417	1570
	S_{40}	798	681	1198	1470
Control	S_{10}	1060	918	1687	1808
Source-2 (APS)	S_{20}	1025	891	1531	1725
	S_{30}	884	815	1367	1545
	S_{40}	711	785	1155	1386
LSD at 5%		65	39	95	120
SEm±		21	13	31	40

§ - Between S_0 and levels S; §§ - Between levels of S

Table 60. Uptake of manganese (kg ha^{-1})

Treatments		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	5.684	5.225	9.217	9.343
	APS	5.423	5.495	8.748	9.278
LSD at 5%		NS	NS	NS	NS
SEm±		0.139	0.171	0.211	0.241
Control	S_0	5.140	4.897	10.590	8.912
Levels of Sulphur (kg ha^{-1}	S_{10}	5.838	5.761	10.17	10.008
	S_{20}	6.050	5.628	9.742	9.806
	S_{30}	5.581	5.422	8.795	9.293
	S_{40}	4.746	4.630	7.217	8.135
LSD at 5%§		0.726	0.884	1.095	1.248
LSD at 5%§§		0.593	0.722	0.894	1.019
SEm±		0.197	0.241	0.298	0.339
Control	S_0	5.140	4.897	10.590	8.912
Source-1 (AS)	S_{10}	6.013	5.720	10.853	10.343
	S_{20}	5.823	5.887	10.147	9.297
	S_{30}	5.583	5.153	8.653	9.116
	S_{40}	5.320	4.140	7.217	8.618
Source-2 (APS)	S_{10}	5.663	5.803	9.500	9.673
	S_{20}	6.277	5.370	9.337	10.315
	S_{30}	5.580	5.690	8.937	9.470
	S_{40}	4.173	5.120	7.217	7.653
LSD at 5%		0.837	1.021	1.265	1.442
SEm±		0.279	0.341	0.422	0.481

§ - Between S_0 and levels of S; §§ - Between levels of S

4.3.4.25 Copper content of grain (ppm)

The copper content of grain is presented in Table 61. The copper contents due to sources were on par in all the trials. Copper content also decreased with higher levels of sulphur. In all the four trials the lowest value of copper in grain was at S_{40}. The copper content in grain in alluvial soil was almost double than that of the copper content in grain of the rice crop grown in brown hydromorphic soil.

4.3.4.26 Copper content of straw (ppm)

The copper content in straw of rice crops of four field trails are presented in Table 62. The copper content at alluvial soil shows that both APS and AS were on par. However, in brown hydromorphic soils in both the seasons the copper content straw in the plots supplied with AS increased than that by APS. In all the four trials the levels significantly influenced the Cu content of straw. In alluvial soil highest level of Cu is present in treatment S_{10} and thereafter the content decreased reaching the lowest values at S_{40}. The copper content in straw of alluvial fields was almost 3 or 4 in times higher than that from brown hydromorphic soil.

4.3.4.27 Uptake of copper (kg ha^{-1})

The uptake of copper in kg ha^{-1} is presented in Table 63. It was seen that both the sources of S were on par. The levels of sulphur significantly influenced the uptake of copper in both locations the lowest uptake was seen at S_{40}. In alluvial soil both *Kharif* and *Rabi* crop showed higher uptake upto 10 kg S ha^{-1}. In *Kharif* and *Rabi* crops of brown hydromorphic soil the highest uptakes were for S_{20} and S_{10} respectively. The uptake of Cu by rice was about 3 times in alluvial soil compared to that in brown hydromorphic soils.

Table 61. Content of copper in grain (ppm)

Treatment		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	12.6	10.3	4.5	6.2
	APS	12.2	9.7	4.3	5.3
LSD at 5%		NS	NS	NS	NS
SEm±		0.2	0.4	0.2	0.4
Control	S_0	13.3	12.3	6.3	6.7
Level of Sulphur (kg ha^{-1})	S_{10}	14.0	11.3	4.8	6.7
	S_{20}	12.7	10.2	4.8	6.3
	S_{30}	12.0	9.3	4.0	5.3
	S_{40}	11.0	9.2	4.0	4.8
LSD at 5%§		1.3	2.1	1.3	2.6
LSD at 5%§§		1.1	1.7	1.1	2.1
SEm±		0.4	0.6	0.4	0.7
Control	S_0	13.3	12.3	6.3	6.7
Source-1 (AS)	S_{10}	14.0	11.7	4.7	7.0
	S_{20}	12.3	10.7	5.0	7.0
	S_{30}	12.3	9.7	4.0	5.7
	S_{40}	11.7	9.3	4.3	5.3
Source-2 (APS)	S_{10}	14.0	11.0	5.0	6.3
	S_{20}	13.0	9.7	4.7	5.6
	S_{30}	11.7	9.0	4.0	5.0
	S_{40}	10.3	9.0	3.7	4.3
LSD at 5%		1.5	2.4	1.5	2.9
SEm±		0.5	0.8	0.5	0.9

§ - Between S_0 and levels of S; §§ - Between levels of S

Table 62. Content of copper in straw (ppm)

Treatment		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	19.3	17.7	5.7	7.3
	APS	18.9	18.8	4.7	5.3
LSD at 5%		NS	NS	0.7	0.9
SEm±		0.4	0.4	0.3	0.3
Control	S_0	23.7	19.0	6.3	7.3
Levels of Sulphur (kg ha^{-1})	S_{10}	24.7	20.2	6.0	7.2
	S_{20}	21.0	18.8	6.5	6.5
	S_{30}	16.5	17.7	4.5	6.0
	S_{40}	14.3	16.5	3.8	5.7
LSD at 5%§		2.3	1.9	1.2	1.6
LSD at 5%§§		1.9	1.6	1.0	1.3
SEm±		0.6	0.5	0.3	0.4
Control	S_0	23.7	19.0	6.3	7.3
Source-1 (AS)	S_{10}	26.0	19.7	7.0	8.0
	S_{20}	19.7	18.3	7.7	7.7
	S_{30}	16.7	17.0	4.7	7.0
	S_{40}	15.0	16.0	3.7	6.7
Source-2 (APS)	S_{10}	23.3	20.7	5.0	6.3
	S_{20}	22.3	19.3	5.3	5.3
	S_{30}	16.3	18.3	4.3	5.0
	S_{40}	13.7	17.0	4.0	4.7
LSD at 5%		2.7	2.3	1.4	1.9
SEm±		0.9	0.8	0.5	0.6

§ - Between S_0 and levels of S; §§ - Between levels of S

Table 63. Uptake of copper (kg ha^{-1})

Treatment		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	0.162	0.146	0.052	0.062
	APS	0.164	0.161	0.046	0.048
LSD at 5%		NS	NS	NS	NS
SEm±		0.004	0.006	0.003	0.005
Control	S_0	0.167	0.137	0.053	0.053
Levels of Sulphur (kg ha^{-1}	S_{10}	0.190	0.163	0.051	0.059
	S_{20}	0.180	0.158	0.059	0.055
	S_{30}	0.151	0.155	0.045	0.057
	S_{40}	0.131	0.138	0.040	0.049
LSD at 5%§		0.021	NS	0.015	NS
LSD at 5%§§		0.017	NS	0.012	NS
SEm±		0.006	0.009	0.004	0.007
Control	S_0	0.167	0.137	0.053	0.053
Source-1 (AS)	S_{10}	0.193	0.157	0.058	0.067
	S_{20}	0.163	0.157	0.006	0.064
	S_{30}	0.153	0.143	0.045	0.061
	S_{40}	0.140	0.130	0.039	0.057
Source-2 (APS)	S_{10}	0.187	0.170	0.045	0.052
	S_{20}	0.197	0.160	0.052	0.047
	S_{30}	0.150	0.167	0.045	0.053
	S_{40}	0.123	0.147	0.041	0.041
LSD at 5%		0.024	NS	0.017	NS
SEm±		0.008	0.013	0.006	0.009

§ - Between S_0 and levels of S; §§ - Between levels of S

4.3.4.28 Removal macronutrients by rice (kg t^{-1})

The uptake of macronutrients @ kg t^{-1} of grain and straw are presented in Table 64. It is seen from the Table that the removal of sulphur, nitrogen and potassium increased with sulphur application (upto 30 kg S ha^{-1}) over control. The uptake of phosphorus and calcium decreased with sulphur application. The ratio of uptake of macronutrients to uptake of S showed that the ratios were narrowed under sulphur application. With regard to the quantity of nutrient removed, the uptake of nitrogen was the highest through grains. The quantity potassium was the highest among the nutrients removed through straw.

4.3.5 Quality of produce

4.3.5.1 Protein content of grain (%)

The protein content of grain is presented in Table 65. It was seen that the protein content of rice crop due to sources were on par except in alluvial soil (*Kharif*). Sulphur application increased protein content. In alluvial soil highest protein content was seen at S_{30} which was statistically on par with S_{20} and S_{40}. At brown hydromorphic soil the protein increased upto S_{30} in both seasons and in *Kharif* crop the superiority of S_{30} over all other levels was significantly seen.

4.3.5.2 Protein content of straw (%)

Protein content of straw is presented in Table 66. APS significantly increased protein content of straw in the *Kharif* season at both locations. However the increase was not statistically significant in the *Rabi* seasons. Protein content in straw significantly increased with sulphur levels from control. In alluvial soil S_{40}

Table 64. Removal of macronutrients by rice (kg t^{-1})

Nutrient		Treatments*	Alluvial soil	Brown hydro-morphic soil	Mean	Ratio to S
A. GRAIN	S	Without S	0.63	0.67	0.65	-
		With S	0.96	0.95	0.95	-
	N	Without S	11.40	11.10	11.25	17.0
		With S	12.80	11.90	12.35	13.0
	P	Without S	2.68	2.69	2.69	4.0
		With S	2.48	2.29	2.39	2.5
	K	Without S	3.63	3.58	3.61	5.5
		With S	4.19	4.15	4.17	4.4
	Ca	Without S	0.42	0.38	0.40	0.6
		With S	0.39	0.34	0.37	0.4
	Mg	Without S	1.19	1.33	1.26	1.9
		With S	1.26	1.27	1.27	1.3
B. STRAW	S	Without S	0.49	0.67	0.58	-
		With S	1.50	1.16	1.33	-
	N	Without S	8.10	7.15	7.63	13.2
		With S	9.35	8.35	8.85	6.6
	P	Without S	1.75	1.62	1.68	2.6
		With S	1.54	1.35	1.44	1.5
	K	Without S	23.60	24.60	24.10	37.1
		With S	26.80	27.50	27.10	28.5
	Ca	Without S	4.70	7.30	6.00	9.0
		With S	3.70	5.80	4.70	5.0
	Mg	Without S	1.40	1.40	1.40	2.2
		With S	1.30	1.40	1.40	1.2

* Without S = Control plot; with S = S @ 30 kg ha^{-1}

Table 65. Protein content of grain (%)

Treatment		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	7.88	7.56	7.38	7.13
	APS	8.19	7.63	7.50	7.13
LSD at 5%		0.32	NS	NS	NS
SEm±		0.11	0.04	0.09	0.07
Control	S_0	6.81	7.44	7.06	6.69
Levels of Sulphur (kg ha^{-1})	S_{10}	7.44	7.56	7.31	7.00
	S_{20}	8.19	7.56	7.50	7.19
	S_{30}	8.31	7.69	7.63	7.25
	S_{40}	8.19	7.56	7.38	7.19
LSD at 5%§		0.54	0.22	0.48	0.33
LSD at 5%§§		0.44	0.18	0.39	0.27
SEm±		0.15	0.06	0.13	0.09
Control	S_0	6.81	7.44	7.06	6.69
Source-1 (AS)	S_{10}	7.25	7.56	7.25	6.94
	S_{20}	8.13	7.56	7.44	7.13
	S_{30}	8.13	7.69	7.44	7.31
	S_{40}	8.00	7.44	7.38	7.19
Source-2 (APS)	S_{10}	7.69	7.63	7.44	7.06
	S_{20}	8.25	7.63	7.50	7.19
	S_{30}	8.56	7.69	7.75	7.19
	S_{40}	8.38	7.69	7.38	7.13
LSD at 5%		0.63	0.25	0.56	0.38
SEm±		0.21	0.08	0.19	0.13

§ - Between S_0 and levels of S; §§ - Between levels of S

Table 66. Protein content of straw (%)

Treatment		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Khari*	*Rabi*
Source of Sulphur	AS	5.63	5.75	4.88	5.00
	APS	5.94	5.88	5.38	5.06
LSD at 5%		0.28	NS	0.25	NS
SEm±		0.09	0.09	0.08	0.10
Control	S_0	5.00	5.13	4.44	4.50
Levels of Sulphur (kg ha^{-1})	S_{10}	5.63	5.69	5.00	4.88
	S_{20}	5.69	5.88	5.19	5.06
	S_{30}	5.81	5.88	5.19	5.25
	S_{40}	6.00	5.88	5.19	4.88
LSD at 5%§		0.49	0.50	0.43	0.51
LSD at 5%§§		0.40	0.41	0.35	0.42
SEm±		0.13	0.14	0.12	0.14
Control	S_0	5.00	5.13	4.44	4.50
Source-1 (AS)	S_{10}	5.56	5.50	4.69	4.88
	S_{20}	5.50	5.88	4.81	5.06
	S_{30}	5.50	5.81	5.00	5.13
	S_{40}	5.88	5.88	4.94	4.94
Source-2 (APS)	S_{10}	5.63	5.88	5.25	4.88
	S_{20}	5.94	5.88	5.50	5.13
	S_{30}	6.06	5.88	5.44	5.38
	S_{40}	6.13	5.88	5.44	4.88
LSD at 5%		0.56	0.58	0.50	0.59
SEm±		0.19	0.19	0.17	0.20

§ - Between S_0 and levels of S; §§ - Between levels of S

recorded higher protein content in straw. In brown hydromorphic soil no increase was seen beyond S_{30}.

4.3.6 Plant growth and soil nutrient relationships

4.3.6.1 Correlation between parameters of yield and uptake of nutrients

The coefficients of correlation between yield parameters and plant nutrients are presented in Tables 67 to 70.

Table 67 shows the correlation coefficients of the *Kharif* crop in alluvial soil. The number of tillers at harvest was positively and significantly correlated to number of productive tillers, total dry matter production, sink capacity, grain yield, straw yield, protein content of grain, protein content of straw, uptake of sulphur, uptake of nitrogen, uptake of phosphorus and uptake of potassium.

Number of productive tillers significantly correlated to dry matter production, sink capacity, grain yield, straw yield, protein content of grain, protein content of straw, uptake of sulphur, uptake of nitrogen and uptake of potassium. Dry matter production significantly correlated to sink capacity, grain yield, straw yield, protein content of grain, protein content of straw, uptake of sulphur, uptake of nitrogen and uptake of potassium. Sink capacity significantly correlated to grain yield, straw yield, protein content of grain, protein content of straw, uptake of sulphur, uptake of nitrogen and uptake of potassium.

Grain yield significantly correlated to straw yield, protein content of grain, protein content of straw, uptake of sulphur, uptake of nitrogen and uptake of potassium. Straw yield significantly correlated to protein content of grain, protein content of straw, uptake of sulphur, uptake of nitrogen and uptake of potassium.

Table 67. Coefficients of correlation between paremeters of yield and uptake of nutrients by rice as influenced by levels sulphur
(Alluvial soil, *Kharif* season)

Parameters	A	B	C	D	E	F	G	H	I	J	K	L
A. Number of tillers at harvest	-	0.8788**	0.8410**	0.8547**	0.8235**	0.7774*	0.8352**	0.9192**	0.8124**	0.9114**	0.6634	0.7935**
B. Number of productive tillers			0.9809**	0.9811**	0.9127**	0.9391**	0.9269**	0.8647**	0.8774**	0.9572**	0.6222	0.9479**
C. Drymatter production				0.9469**	0.8320**	0.9694**	0.9510**	0.8111**	0.8764**	0.9659**	0.6090	0.9721**
D. Sink capacity					0.9218**	0.8870**	0.8941**	0.8212**	0.7939*	0.9160**	0.6398	0.8984**
E. Grain yield						0.9137**	0.8779**	0.7261*	0.9392**	0.9229**	0.0109	0.9021**
F. Straw yield							0.9204**	0.7973*	0.9310**	0.9255**	0.4260	0.9909**
G. Protein content of grain								0.8286**	0.8996**	0.9741**	0.4934	0.9523**
H. Protein content of straw									0.8727**	0.9036**	0.4233	0.8354**
I. Uptake of sulphur										0.8995**	0.3200	0.9296**
J. Uptake of nitrogen											0.5777	0.9511**
K. Uptake of phosphorus												0.4358
L. Uptake of potassium												-

* Significant at 5% level
** Significant at 1% level

Protein content of grain significantly correlated protein content of straw uptake of sulphur, uptake of nitrogen and uptake of potassium. Protein content of straw significantly correlated to uptake of sulphur, uptake of nitrogen and uptake of potassium. Uptake of sulphur significantly correlated to uptake of nitrogen and uptake of potassium. Uptake of potassium significantly correlated to uptake of potassium.

Table 68 shows correlation coefficients between parameters of yield and nutrient uptake of alluvial soil in *Rabi* season. It is seen that number of tillers is significantly correlated to number of productive tillers, and grain yield. Number of productive tillers significantly correlated to dry matter production, sink capacity, grain yield, straw yield protein content of grain, uptake of nitrogen and uptake of potassium. Sink capacity significantly correlated to grain yield, straw yield, protein content of straw, uptake of sulphur, uptake of nitrogen and uptake of potassium. Grain yield significantly correlated to straw yield, protein content of grain, protein uptake of sulphur, uptake of nitrogen and uptake of potassium.

Straw yield significantly correlated to protein content of straw, uptake of sulphur, uptake of nitrogen and uptake of potassium. Protein content of grain significantly correlated to uptake of nitrogen, protein content of straw significantly correlated to uptake of sulphur uptake of nitrogen and uptake of potassium. Uptake of sulphur significantly correlated to uptake of nitrogen and uptake of potassium uptake of nitrogen significantly correlated to uptake of potassium.

Table 69 shows correlation coefficients for growth parameters and uptake of nutrients in brown hydromorphic soil for *Kharif* season. It was seen that number of tillers at harvest, number and productive tillers, and dry matter production correlated with all other parameters mentioned except protein content of straw and

Table 68. Coefficients of correlation between parameters of yield and uptake of nutrients by rice as influenced by levels of sulphur
(Alluvial soil, *Rabi* season)

Parameters	A	B	C	D	E	F	G	H	I	J	K	L
A. Number of tillers at harvest	-	0.9186**	0.4889	0.6466	0.7269*	0.5226	0.3138	0.6101	0.2016	0.5268	0.6862*	0.3029
B. Number of productive tillers			0.9186**	0.9246**	0.9225**	0.8733**	0.7029*	0.7029**	0.8742**	0.9498*	0.2224	0.8912**
C. Drymatter production				0.8492**	0.9015**	0.9858**	0.7082*	0.8833**	0.8992**	0.9924**	0.3765	0.9645**
D. Sink capacity					0.8929**	0.8284**	0.5931	0.8850**	0.8266**	0.8802**	0.2249	0.8348**
E. Grain yield						0.9020**	0.7859*	0.6520	0.9010**	0.8925**	0.2217	0.9210**
F. Straw yield							0.6640	0.8646**	0.8673**	0.9727**	0.4196	0.9409**
G. Protein content of grain								0.5692	0.6460	0.7282*	0.4132	0.6652
H. Protein content of straw									0.8291**	0.9269**	0.1921	0.8472**
I. Uptake of sulphur										0.9030**	-0.0046	0.9779**
J. Uptake of nitrogen											0.3470	0.9548**
K. Uptake of phosphorus												0.1662
L. Uptake of potassium												-

* Significant at 5% level
** Significant at 1% level

Table 69. Coefficients of correlation between parameters of yield and uptake of nutrients by rice as influenced by levels of sulphur
(Brown hydromorphic soil, *Kharif* season)

Parameters	A	B	C	D	E	F	G	H	I	J	K	L
A. Number of tillers at harvest	-	0.9044**	0.8457**	0.7738*	0.8480**	0.7867*	0.8672**	0.4237	0.7943*	0.9151**	0.5358	0.7408*
B. Number of productive tillers			0.9661**	0.8311**	0.9210**	0.9333**	0.9161**	0.6207	0.9165**	0.9578**	0.3516	0.9316**
C. Drymatter production				0.7813*	0.9532**	0.9847**	0.8811**	0.5946	0.9047**	0.9532**	0.3947	0.9438**
D. Sink capacity					0.9212**	0.7421	0.7760*	0.7062*	0.8283*	0.8445**	0.4246	0.7858**
E. Grain yield						0.9722**	0.9327**	0.6525	0.9226**	0.8927**	0.1620	0.9215**
F. Straw yield							0.8311**	0.5097	0.8774**	0.8994**	0.3700	0.9246**
G. Protein content of grain								0.6016	0.7963*	0.9354**	0.5220	0.8135**
H. Protein content of straw									0.7420*	0.6840*	-0.2267	0.7612*
I. Uptake of sulphur										0.9256**	0.0515	0.9731**
J. Uptake of nitrogen											0.3921	0.9166**
K. Uptake of phosphorus												0.0925
L. Uptake of potassium												-

* Significant at 5% level
** Significant at 1% level

phosphorus uptake. Sink capacity correlated with parameters except phosphorus uptake. Grain yield, straw yield, and protein content of grain correlated with all parameters except protein content of straw and phosphorus uptake. Protein content of straw correlated to uptake of sulphur, uptake of nitrogen and uptake of potassium. Uptake of sulphur correlated to uptake of nitrogen and uptake of potassium. Uptake of nitrogen correlated to uptake of potassium.

Table 70 shows correlation co-efficients of growth parameters and uptake of nutrients in brown hydromorphic soil for *Rabi* season. It is seen that number of tillers, number of productive tillers, dry matter production, sink capacity, grain yield, straw yield, protein content of grain, protein content of straw uptake of sulphur, uptake of nitrogen and uptake of potassium correlated between them mutually. Phosphorus uptake did not possess any significant correlation with the other parameters.

4.3.6.2 Agronomic efficiency of rice (kg kg^{-1})

Agronomic efficiency is presented in Table 71. It was seen that APS significantly increased the agronomic efficiency of rice compared to AS. There was significant reduction in agronomic efficiency by higher levels of sulphur application. The lower levels (viz. S_{10} and S_{20}) were on par and S_{40} significantly reduced agronomic efficiency over that in S_{10}.

4.3.6.3 Physiological efficiency (kg kg^{-1})

Mean values of physiological efficiency (Table 72) due to sources were at par except at *Kharif* season in brown hydromorphic soil where a higher physiological efficiency was found with AS compared to APS. Levels of sulphur showed that

Table 70. Coefficients of correlation between parameters of yield and uptake of nutrients by rice as influenced by levels of sulphur
(Brown hydromorphic soil, *Rabi* season)

Parameters	A	B	C	D	E	F	G	H	I	J	K	L
A. Number of tillers at harvest	-	0.8494**	0.8708**	0.7786*	0.8479**	0.8587**	0.7337*	0.8355**	0.7296*	0.8576**	0.2390	0.8233**
B. Number of productive tillers			0.9368**	0.9101**	0.9089**	0.9016**	0.9503**	0.9224**	0.9044**	0.9541**	-0.0756	0.8871**
C. Drymatter production				0.8773**	0.9199**	0.9599**	0.8913**	0.9460**	0.9010**	0.9861**	0.0108	0.9661**
D. Sink capacity					0.9605**	0.7766*	0.8959**	0.8254**	0.9164**	0.9111**	-0.2725	0.8579**
E. Grain yield						0.9219**	0.8360**	0.9050**	0.8838**	0.9395**	-0.0308	0.8821**
F. Straw yield							0.8276**	0.9235**	0.8374**	0.9584**	0.1007	0.9235**
G. Protein content of grain								0.8283**	0.8824**	0.9009**	-0.2948	0.8500**
H. Protein content of straw									0.7871*	0.9616**	0.2088	0.8461**
I. Uptake of sulphur										0.9016**	-0.3337	0.9516**
J. Uptake of nitrogen											-0.0104	0.9391**
K. Uptake of phosphorus												-0.1287
L. Uptake of potassium												-

* Significant at 5% level
** Significant at 1% level

Table 71. Agronomic efficiency of rice (kg kg^{-1})

Treatments		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	17.75	18.33	16.63	18.16
	APS	27.05	30.92	25.92	25.78
LSD at 5%		5.93	5.39	4.67	5.11
SEm±		1.97	1.79	1.56	1.70
Control	S_0	-	-	-	-
Level of Sulphur (kg ha^{-1})	S_{10}	30.50	32.16	28.34	27.50
	S_{20}	30.00	28.67	25.02	26.25
	S_{30}	19.50	24.33	20.28	21.65
	S_{40}	9.67	13.33	11.46	12.08
LSD at 5%		8.38	7.63	6.62	7.23
SEm±		2.79	2.54	2.21	2.41
Control	S_0	-	-	-	-
Source-1 (AS)	S_{10}	23.33	19.33	15.86	21.67
	S_{20}	21.33	23.67	21.28	24.17
	S_{30}	18.67	19.00	19.17	17.22
	S_{40}	7.67	11.33	10.21	9.58
Source-2 (APS)	S_{10}	37.67	45.00	40.83	33.33
	S_{20}	38.67	33.67	28.75	28.33
	S_{30}	20.33	29.67	21.39	26.09
	S_{40}	11.67	15.33	12.71	14.58
LSD at 5%		11.86	10.78	9.35	10.22
SEm±		3.96	3.59	3.12	3.41

Table 72. Physiological efficiency of rice (kg ha^{-1})

Treatment		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	205	383	394	293
	APS	202	324	314	328
LSD at 5%		NS	NS	61	NS
SEm±		9	23	20	24
Control	S_0	-	-	-	-
Levels of Sulphur (kg ha^{-1})	S_{10}	215	419	388	313
	S_{20}	236	384	393	383
	S_{30}	208	320	349	334
	S_{40}	156	293	287	213
LSD at 5%		40	99	87	103
SEm±		13	33	29	34
Control	S_0	-	-	-	-
Source-1 (AS)	S_{10} 216	433	456	325	
	S_{20}	219	416	437	341
	S_{30}	209	348	400	318
	S_{40}	176	335	282	189
Source-2 (APS)	S_{10}	213	404	319	301
	S_{20}	252	351	348	424
	S_{30}	207	292	298	350
	S_{40}	136	250	291	237
LSD at 5%		54	141	123	146
SEm±		18	47	41	48

except at one trial (*Rabi* in alluvial) in all the three trials physiological efficiency reached high at S_{20} there after it declined. However, all the three levels S_{10}, S_{20} and S_{30} were on par in all the four trials. S_{40} showed the lowest physiological efficiency.

4.3.6.4 Apparent recovery efficiency (%)

Apparent recovery efficiency is presented in Table 73. It was seen that apparent recovery efficiency was more for APS compared to AS and it was significantly higher in the three trials except *Rabi* crop in brown hydromorphic soil. The apparent recovery efficiency declined when the sulphur level increased. The highest recovery was seen with low level of sulphur and the lowest recovery percentage with S_{40}.

4.3.6.5 Response ratio of total biomass (kg ha^{-1})

The response ratio of total biomass and per cent increase are presented in Table 74. It was seen that the response ratio declined with increase in higher levels of sulphur showing the highest values for S_{10} and lowest at S_{40}. The per cent increase of biomass increased upto S_{30} and thereafter declined.

4.3.6.6 Per cent yield of rice

Table 75 shows per cent yield of rice, per cent increase in yield and response ratio of rice. The per cent yield and per cent increase in yield showed that these values increased with levels of sulphur. The maximum values were seen at S_{30} and at S_{40} it declined. The response ratios showed that the ratios declined with increase in sulphur doses.

Table 73. Apparent recovery efficiency (%)

Treatment		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	29.33	19.33	18.75	16.25
	APS	36.16	27.92	24.16	18.58
LSD at 5%		4.63	5.27	4.31	4.47
SEm ±		1.54	1.76	1.43	1.48
Control	S_0	-	-	-	-
Levels of Sulphur ($kg\ ha^{-1}$)	S_{10}	44.00	31.50	27.34	24.5
	S_{20}	34.66	25.34	21.33	16.84
	S_{30}	27.83	20.83	20.50	16.00
	S_{40}	24.50	16.83	16.67	12.33
LSD at 5%		6.54	7.45	6.09	6.32
SEm ±		2.18	2.48	2.03	2.10
Control	S_0	-	-	-	-
Source-1 (AS)	S_{10}	36.33	26.33	25.67	23.67
	S_{20}	31.00	23.67	19.00	14.67
	S_{30}	26.33	14.33	16.67	14.33
	S_{40}	23.67	13.00	13.67	12.33
Source-2 (APS)	S_{10}	51.67	36.67	29.00	25.33
	S_{20}	38.33	27.00	23.67	19.00
	S_{30}	29.33	27.33	24.33	17.67
	S_{40}	25.33	20.67	19.67	12.33
LSD at 5%		9.25	10.54	8.62	8.93
SEm ±		3.08	3.51	2.87	2.90

Table 74. Response ratio of total biomass of rice (kg kg^{-1} S)

Location/ season	Parameters	Added S kg ha^{-1})				
		0	10	20	30	40
	Biomass yield	8591	9557	10203	10342	10067
Alluvial soil (*Kharif*)	Per cent yield	100	111	118	120	117
	Per cent increase	-	11	18	20	17
	Response ratio	-	97	80	58	40
	Biomass yield	8383	9766	10382	10516	10166
Alluvial soil (*Rabi*)	Per cent yield	100	116	124	125	121
	Per cent increase	-	16	24	25	21
	Response ratio	-	138	100	71	45
	Biomass yield	8541	9657	10174	10559	10099
Brown hydromor-phic soil (*Kharif*)	Per cent yield	100	113	119	124	118
	Per cent increase	-	13	19	24	18
	Response ratio	-	112	82	67	39
	Biomass yield	8033	8774	9391	9624	9207
Brown hydromor-phic soil (*Rabi*)	Per cent yield	100	119	117	120	115
	Per cent increase	-	9	17	20	15
	Response ratio	-	74	68	53	29
	Biomass yield	8387	9439	10192	10260	9885
Mean	Per cent yield	100	112	120	122	118
	Per cent increase	-	12	20	22	18
	Response ratio	-	105	83	62	38

Table 75. Per cent yield of rice

Location/ season	Parameter	Added sulphur (kg ha^{-1})				
		0	10	20	30	40
Alluvial soil (*Kharif*	Grain yield (kg ha^{-1})	4008	4312	4608	4591	4400
	Per cent yield	100	108	115	115	110
	Per cent increase	-	8	15	15	10
	Response ratio	- .	30	30	19	10
Alluvial soil (*Rabi*)	Grain yield (kg ha^{-1})	3700	4016	4266	4433	4233
	Per cent yield	100	109	115	120	114
	Per cent increase	-	9	15	20	14
	Response ratio	-	32	28	24	13
Brown hydromorphic soil (*Kharif*)	Grain yield (kg ha^{-1})	4008	4291	4508	4616	4466
	Per cent yield	100	107	112	115	111
	Per cent increase	-	7	12	15	11
	Response ratio	-	28	25	20	11
Brown hydromorphic soil (*Rabi*)	Grain yield (kg ha^{-1})	3383	3658	3908	4033	3866
	Per cent yield	100	108	116	119	114
	Per cent increase	-	8	16	19	14
	Response ratio	-	28	26	22	12
Mean	Grain yield (kg ha^{-1})	3775	4069	4322	4418	4241
	Per cent yield	100	108	115	117	112
	Per cent increase	-	8	15	17	12
	Response ratio	-	29	27	21	12

4.3.7 Economics of sulphur nutrition

4.3.7.1 Gross income from rice crop (Rs. ha^{-1})

The gross income worked out per hectare for rice cultivation under sulphur levels is presented in Table 76. The gross income increased by APS compared to that by AS in all the four experiments. Higher levels of sulphur application increased the gross income upto S_{30} but except in *Rabi* at brown hydromorphic soil the increase in gross income was found to be significant upto S_{20}. The income declined at S_{40}. The income from control (S_0) was the least and significantly low.

4.3.7.2 Net return from rice (Rs. ha^{-1})

The net return from rice is presented in Table 77. It was seen that the net return was higher for APS over AS and the mean value were significantly higher in two trials. During *Kharif* season at alluvial soil highest net return was obtained at S_{20}. However, in other 3 field experiments the increase were seen upto S_{30}. The highest dose of sulphur declined net return. The net return by control plot was significantly low, in all field experiments.

4.3.7.3 Benefit : cost ratio

The benefit : cost ratio is presented in Table 78. The benefit : cost ratio was significantly high for APS than for AS in the *Rabi* season in both locations. The benefit : cost ratio followed the pattern of net return and the higher levels of sulphur increased benefit : cost ratio followed by decrease with highest level of sulphur (S_{40}). The increases in B : C ratio were significant upto S_{20}.

Table 76. Gross income from rice crop (Rs.)

Treatment		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	20337	20765	20323	19072
	APS	21062	21995	20947	19820
LSD at 5%		583	547	617	392
SEm±		194	182	205	130
Control	S_0	18325	18350	18300	17000
Levels of Sulphur (kg ha^{-1})	S_{10}	19873	20320	19850	18435
	S_{20}	21231	21590	20867	19605
	S_{30}	21262	22270	21437	20300
	S_{40}	20433	21340	20587	19185
LSD at 5%§		1009	946	1068	678
LSD at 5%§§		824	773	872	554
SEm±	275	257	291	184	
Control	S_0	18325	18350	18300	17000
Source-1 (AS)	S_{10}	19545	19670	19417	18250
	S_{20}	20500	21240	20600	19250
	S_{30}	21120	21300	21241	19650
	S_{40}	20183	20850	20433	19140
Source-2 (APS)	S_{10}	20200	20970	20283	18620
	S_{20}	21962	21940	21133	19960
	S_{30}	21404	23240	21633	20950
	S_{40}	20683	21830	20741	19750
LSD at 5%		1166	1093	1234	783
SEm±		389	365	412	261

§ - Between S_0 and levels of S; §§ - Between levels of S

Table 77. Net return from rice (Rs.)

Treatment		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	8599	8521	8983	7033
	APS	9103	9481	9321	7593
LSD at 5%		NS	540	NS	391
SEm±		206	180	206	130
Control	S_0	6891	6416	7166	5266
Levels of Sulphur (kg ha^{-1})	S_{10}	8279	8049	8556	6541
	S_{20}	9478	9328	9414	7552
	S_{30}	9284	9857	9824	8087
	S_{40}	8361	8768	8815	7073
LSD at 5%§		1069	934	1060	678
LSD at 5%§§		873	763	873	554
SEm±		291	254	291	184
Control	S_0	6891	6416	7166	5266
Source-1 (AS)	S_{10}	7970	7694	8160	6394
	S_{20}	8822	9062	9223	7272
	S_{30}	9321	9000	9740	7550
	S_{40}	8261	8428	8811	6918
Source-2 (APS)	S_{10}	8569	8505	8952	6689
	S_{20}	10134	9595	9605	7832
	S_{30}	9247	10715	9908	8625
	S_{40}	8461	9108	8819	7228
LSD at 5%		1234	1080	1234	783
SEm±		411	360	411	261

§ - Between S_0 and levels of S; §§ - Between levels of S

Table 78. Benefit:Cost Ratio

Treatment		Alluvial soil		Brown hydromorphic soil	
		Kharif	*Rabi*	*Kharif*	*Rabi*
Source of Sulphur	AS	1.728	1.693	1.781	1.579
	APS	1.763	1.764	1.798	1.617
LSD at 5%		NS	0.045	NS	0.032
SEm±			0.015		0.011
Control	S_0	1.600	1.533	1.640	1.446
Levels of Sulphur (kg ha^{-1})	S_{10}	1.710	1.675	1.752	1.543
	S_{20}	1.803	1.757	1.818	1.623
	S_{30}	1.778	1.790	1.842	1.658
	S_{40}	1.692	1.692	1.745	1.567
LSD at 5%§		0.083	0.007	0.094	0.056
LSD at 5%§§		0.068	0.063	0.077	0.046
SEm±		0.022	0.021	0.025	0.015
Control	S_0	1.600	1.533	1.640	1.446
Source-1 (AS)	S_{10}	1.687	1.627	1.720	1.538
	S_{20}	1.753	1.737	1.806	1.603
	S_{30}	1.783	1.733	1.843	1.620
	S_{40}	1.690	1.673	1.753	1.560
Source-2 (APS)	S_{10}	1.733	1.723	1.783	1.553
	S_{20}	1.853	1.777	1.830	1.643
	S_{30}	1.773	1.847	1.840	1.697
	S_{40}	1.693	1.710	1.737	1.573
LSD at 5%		0.097	0.090	0.108	0.065
Sem±		0.032	0.030	0.036	0.022

§ - Between S_0 and levels of S; §§ - Between levels of S

4.3.7.4 Pooled analysis of yield and economics

The effect of sulphur application on yield and economics over locations and seasons are presented in Table 79. It was seen from the pooled analysis of four field experiments that APS significantly increased grain yield over AS. The increase in straw yield by APS was not significant and both were on par. With respect to net return (Rs. ha^{-1}) APS gave more net returns. A profit of Rs.510/- per hectare was obtained per hectare when APS was preferred over AS. The B : C ratio of APS was higher that of AS. Among the levels S_{30} gave highest grain and straw yields but it was on par with S_{20}. Similarly, though net return and B : C ratio were high for S_{30}, it was found statistically on par. The source x level table showed that even though S_{30} under APS and AS are having the highest values of grain yield, straw yield, net return and B : C ratio both S_{20} and S_{30} were on par which led to the need for studying optimum and economic levels between the two.

4.3.7.5 Response surface and optimum levels

As the control vs treatment was significant and there was progressive increase in grain yield by addition of sulphur upto 30 kg S ha^{-1} correlations and regressions were worked out and presented. Quadratic regression ($Y = a + bX + cX^2$) was fitted for grain yield (Y) in relation to sulphur levels (X) for both sources under two locations and two seasons. The response equation and optimum levels are presented in Table 80. It is seen than from the table that the physical optimum levels of AS and APS for *Kharif* season in alluvial soil were 26.43 and 25.34 kg S ha^{-1}. The corresponding economic optimum levels were 24.85 and 23.06 kg S ha^{-1}. The physical optimum levels of AS and APS for *Rabi* season at alluvial soil were 31.47

Table 79. Effect of sulphur application on grain yield (kg ha^{-1}), straw yield (kg ha^{-1}), Net return (Rs. ha^{-1}) and Benefit:Cost Ratio (Pooled analysis of locations and seasons)

Treatment		Grain yield kg ha^{-1}	Straw yield kg ha^{-1}	Net return Rs. ha^{-1}	Benefit: Cost ratio
Source of Sulphur	AS	4076	5595	8285	1.69
	APS	4354	5696	8875	1.74
LSD at 5%		57	NS	291	0.03
SEm±		19	75	97	0.01
Control	S_0	3775	4613	6435	1.56
Levels of Sulphur (kg ha^{-1})	S_{10}	4070	5370	7857	1.67
	S_{20}	4323	5716	8944	1.75
	S_{30}	4419	5852	9264	1.76
	S_{40}	4241	5644	8255	1.67
LSD at 5%§		99	362	504	0.04
LSD at 5%§§		80	296	412	0.04
SEm±		26	98	137	0.01
Control	S_0	3775	4613	6435	1.56
Source-1 (AP)	S_{10}	3973	5369	7535	1.64
	S_{20}	4225	5713	8595	1.73
	S_{30}	4329	5648	8903	1.74
	S_{40}	4162	5650	8105	1.67
Source-2 (APS)	S_{10}	4167	5371	8179	1.70
	S_{20}	4421	5719	9292	1.78
	S_{30}	4508	6056	9624	1.79
	S_{40}	4320	5638	8404	1.68
LSD at 5%		114	419	583	0.05
SEm±		40	149	207	0.02
Alluvial		4301	5646	8673	1.72
Brown hydromorphic		4116	5415	8009	1.68
LSD at 5%		53	197	274	0.02
SEm±		19	70	97	0.01
Kharif season		4423	5496	8782	1.74
Rabi season		3995	5565	7900	1.64
LSD at 5%		53	NS	274	0.02
SEm±		19	70	97	0.01

§ - Between S_0 and levels of S; §§ - Between levels of S

Table 80. Response equation and optimum levels of sulphur in alluvial and brown hydromorphic soils

Soil, season and source	Equation	R^2	Physical optimum kg ha^{-1}	Economic optimum kg ha^{-1}
Alluvial-*Kharif* (Amm.Sulphate)	$Y_{S1} = 3978.57 + 38.7028\ S - 0.7322\ S^2$	0.73	26.43	24.85
Alluvial-*Kharif* (Ammonium Phosphate Sulphate)	$Y_{S2} = 3993.571 + 56.1191\ S - 1.1071\ S^2$	0.70	25.34	23.06
Alluvial-*Rabi* (AS)	$Y_{S1} = 3664.764 + 35.2139\ S - 0.5595\ S^2$	0.76	31.47	28.73
Alluvial-*Rabi* (APS)	$Y_{S2} = 3682.857 + 58.2619\ S - 1.0357\ S^2$	0.80	28.12	25.80
Brown hydromorphic *Kharif* (AS)	$Y_{S1} = 3965.476 + 34.23815\ S - 0.5476\ S^2$	0.73	31.26	28.33
Brown hydromorphic *Kharif* (APS)	$Y_{S2} = 4015.952 + 46.3095\ S - 0.8452\ S^2$	0.75	27.39	24.41
Brown hydromorphic *Rabi* (AS)	$Y_{S1} = 3356.666 + 37.3335\ S - 0.6667\ S^2$	0.82	27.99	25.71
Brown hydromorphic *Rabi* (APS)	$Y_{S2} = 3358.572 + 47.1191\ S - 0.7738\ S^2$	0.83	30.45	27.34

Economic optimum level has been worked out on the basis of price structure estimated from the cost of related fertilizers

1 kg N as urea	- Rs.7.39
1 kg P_2O_5 as mussoriephos	- Rs.8.85
1 kg N as ammonium sulphate	- Rs.7.39
1 kg N as ammonium phosphate sulphate	- Rs.7.39
1 kg P_2O_5 as ammonium phosphate sulphate	- Rs.8.85
1 kg sulphur as ammonium sulphate	- Rs.12.84
1 kg sulphur as ammonium phosphate sulphate	- Rs.20.20

and 28.12 kg S ha^{-1}. The corresponding economic optimum levels were 28.73 and 25.80 kg S ha^{-1}. The physical otipmum levels of AS and APs for *Kharif* season at brown hydromorphic soil were 31.26 and 27.39 kg S ha^{-1}. The corresponding economic optimum levels were 28.33 and 24.41 kg S ha^{-1}. The physical optimum levels of AS and APS estimated for *Rabi* crop at brown hydromorphic soils were 27.99 and 30.45 kg S ha^{-1}. The corresponding economic optimum levels were 25.71 and 27.34 kg S ha^{-1}. From the pooled mean data of grain yield the response equation and the optimum levels of S as AS and APS have been worked out and presented below:

(a) Ammonium sulphate

$Y_{S1} = 3741.372 + 36.3857\ S - 0.6271\ S^2\ (R^2 = 0.9449097)$

Physical optimum level = 29.00 kg S ha^{-1}

Economic optimum level = 26.75 kg S ha^{-1}

(b) Ammonium phosphate sulphate

$Y_{S2} = 3762.429 + 52.2243\ S - 0.9479\ S^2\ (R^2 = 0.9940957)$

Physical optimum level = 27.55 kg S ha^{-1}

Economic optimum level = 24.90 kg S ha^{-1}

4.3.8 Residual effect of sulphur on succeeding crop

The mean values are presented in Table 81. The residual effect was significant only in grain yield at brown hydromorphic soils. The crop raised with APS showed significantly higher yield of grain over AS. In the same location grain yield increased significantly over control plots by S_{30} and S_{40}. The plots received 10, 20 and 30 kg S ha^{-1} were on par. The plot received S @ 40 kg ha^{-1} gave significantly higher grain yield over the rest. The plot received S @ 10 and 20 kg in previous season are on par with control.

Table 81. Residual effect of sulphur on succeeding crop

Treatment		Alluvial soil		Brown hydromorphic soil	
		Grain yield	Straw yield	Grain yield	Straw yield
Source of Sulphur	AS	3792	4800	3406	4791
	APS	3850	4771	3583	4867
LSD at 5%		NS	NS	53	NS
SEm±		40	47	17	63
Control	S_0	3666	4683	3400	4583
Levels of Sulphur (kg ha^{-1})	S_{10}	3733	4767	3433	4617
	S_{20}	3765	4708	3475	4783
	S_{30}	3825	4775	3542	4917
	S_{40}	3958	4892	3649	4999
LSD at 5%§		NS	NS	92	NS
LSD at 5%§§		NS	NS	75	NS
SEm±		56	66	25	90
Control	S_0	3666	4683	3400	4583
Source-1 (AS)	S_{10}	3733	4850	3416	4600
	S_{20}	3750	4700	3450	4716
	S_{30}	3783	4800	3483	4883
	S_{40}	3900	4850	3516	4966
Source-2 (APS)	S_{10}	3733	4683	3450	4633
	S_{20}	3783	4716	3500	4850
	S_{30}	3866	4750	3600	4950
	S_{40}	4016	4933	3783	5033
LSD at 5%		NS	NS	106	NS
SEm±		80	93	35	127

§ - Between S_0 and levels of S; §§ - Between levels of S

4.4 Part-IV. Sulphur use efficiency of rice

4.4.1 Specific activity (dpm μg^{-1} S)

The specific activities of ^{35}S in rice cultured in alluvial and brown hydromorphic soils and their pooled analysis are presented in Table 82.

In alluvial soil the specific activities showed that the specific activity of APS was significantly higher in grain than that of AS. In straw both were on par. The specific activity of S in whole plant also showed that it was more in APS received plants.

With regard to levels of S the specific activities in grain straw and whole plant were significantly varied by different levels of ^{35}S. Compared to straw the specific activity was more in grain at lower levels of 10 and 20 kg S ha^{-1}. The specific activities increased with sulphur levels upto the highest level of ^{35}S. The specific activities in S_{30} and S_{40} were on par.

In brown hydromorphic soil the specific activity in grain and whole plant were higher in APS applied plants compared to AS applied ones. The levels showed that specific activity in grain, straw and whole plant increased with increase in sulphur dose.

The pool analysis of both soils showed that specific activities of grain and whole plant in pots received ^{35}S tagged APS gave higher specific activity than those received the AS source of ^{35}S. The higher sulphur levels increased specific activity and maximum activity was seen in S_{40}.

Table 82. Specific activities (dpm μg^{-1} S) in relation to applied sulphur (^{35}S)

Treatment		Rice cultured in Alluvial soil			Rice cultured in Brown hydromorphic			Both soils (pooled)		
		Grain	Straw	Whole plant	Grain	Straw	Whole plant	Grain	Straw	Whole plant
Source of Sulphur	AS	42.25	46.85	44.27	40.35	41.59	41.25	41.31	44.22	42.75
	APS	51.73	46.41	49.71	49.67	45.48	47.44	50.70	45.95	48.57
LSD at 5%		8.10	NS	4.81	5.69	NS	3.07	4.91	NS	2.78
SEm±		2.67	1.45	1.56	1.87	1.31	1.01	1.63	0.93	0.92
Level of Sulphur (kg ha^{-1})	S_{10}	27.18	26.80	27.36	24.78	23.89	24.80	25.98	25.34	26.08
	S_{20}	47.73	43.84	46.21	40.26	41.69	40.88	43.99	42.77	43.55
	S_{30}	53.49	55.05	54.40	53.46	52.64	53.10	53.48	53.84	53.75
	S_{40}	59.57	60.84	59.96	61.56	55.94	58.60	60.56	58.39	59.28
LSD at 5%		11.46	6.21	6.80	8.05	5.61	4.34	6.94	3.93	3.93
SEm±		3.77	2.04	2.24	2.65	1.85	1.43	2.31	1.31	1.31
S_{10} as AS		21.33	28.59	24.50	24.26	20.72	23.76	22.79	24.65	24.13
S_{20} as AS		42.83	46.38	44.67	34.09	42.47	38.10	38.46	44.43	41.38
S_{30} as AS		48.99	53.34	50.83	50.00	50.60	60.26	49.50	51.97	50.55
S_{40} as AS		55.87	59.11	57.06	53.05	52.60	52.86	54.46	55.85	54.96
S_{10} as APS		33.03	25.02	30.23	25.30	27.06	25.83	29.16	26.04	28.03
S_{20} as APS		52.62	41.29	47.76	46.42	40.92	43.66	49.52	41.10	45.71
S_{30} as APS		58.00	56.76	57.96	56.91	54.67	55.93	57.45	55.72	56.95
S_{40} as APS		63.26	62.57	62.86	70.06	59.28	64.33	66.66	60.92	63.60
LSD at 5%		16.21	8.78	9.62	11.39	7.93	6.14	9.81	5.55	5.56
SEm±		5.34	2.89	3.17	3.75	2.61	2.02	3.27	1.85	1.85
Alluvial soil								46.99	46.63	46.98
Brown hydromorphic soil								45.01	43.54	44.34
LSD at 5%								NS	2.77	NS
SEm±								1.63	0.92	0.93

The specific activities in plants grown in alluvial and brown hydromorphic soils showed that specific activity in straw was high in plants cultured in alluvial.

4.4.2 Rice yield and sulphur uptake by levels of S applied as ^{35}S

The data is presented in Tables 83 to 85. It was seen that in alluvial soil (Table 83) AS and APS were on par in grain yield, straw and total drymatter yield. The removal of sulphur through grain, straw and whole plant showed that these three were significantly more in APS applied pot than that in AS applied pots.

The effects of increased levels of sulphur application showed increase in yield of grain, straw and total drymatter production upto S_{30}. The increase in sulphur by grain increased upto S_{30} where the increase in straw and total drymatter production progressed upto highest level tried (S_{40}).

In brown hydromorphic soil (Table 84) the grain yield, straw yield and total drymatter yield significantly increased in APS source compared to AS source of ^{35}S. The higher levels sulphur increased the grain yield, straw yield and dry matter yield. The total grain S, straw S and total S uptake also increased by APS source compared to AS source. The higher levels of sulphur increased the uptake of sulphur in grain, straw and total plant.

The pooled analysis of results of both the soils showed that APS increased straw yield and total yield compared to AS. The removal of S through grain, straw and total plant also increased by APS over those by AS.

Table 83. Rice yield and uptake of S as influenced by levels of sulphur applied as ^{35}S

Treatment		Rice cultured in alluvial soil					
		Grain yield (g pot^{-1})	Straw yield (g pot^{-1})	Total drymatter (g pot^{-1})	Total grain sulphur (mg pot^{-1})	Total straw S (mg pot^{-1})	Total S uptake (mg pot^{-1})
Source of Sulphur	AS	8.64	12.68	21.21	10.80	16.71	27.52
	APS	8.33	12.81	21.14	11.72	18.68	30.47
LSD at 5%		NS	NS	NS	0.68	1.34	1.30
SEm±		0.14	0.14	0.16	0.23	0.45	0.43
Control	S_0	7.30	10.07	17.37	5.23	7.92	13.16
^{35}S levels (kg ha^{-1})	S_{10}	8.18	12.22	20.17	8.77	13.85	22.62
	S_{20}	8.80	12.80	21.60	11.18	16.28	27.47
	S_{30}	8.85	13.10	21.95	12.85	19.39	32.37
	S_{40}	8.12	12.87	20.98	12.25	21.25	33.51
LSD at 5%§		0.68	0.71	0.80	1.18	2.32	2.25
LSD at 5%§§		0.56	0.58	0.66	0.97	1.90	1.84
SEm±		0.18	0.19	0.22	0.32	0.63	0.61
Control	S_0	7.30	10.07	17.37	5.23	7.92	13.16
Source-1 (AS)	S_{10}	8.37	12.27	20.17	9.12	13.37	22.48
	S_{20}	8.87	12.77	21.63	10.98	15.46	26.45
	S_{30}	8.90	12.97	21.87	11.85	18.35	30.19
	S_{40}	8.43	12.73	21.17	11.27	19.66	30.93
Source-2 (APS)	S_{10}	8.00	12.17	20.17	8.42	14.34	22.76
	S_{20}	8.73	12.83	21.57	11.37	17.12	28.49
	S_{30}	8.80	13.23	22.03	13.85	20.43	34.55
	S_{40}	7.80	13.00	20.80	13.23	22.85	36.08
LSD at 5%		0.80	0.82	0.93	1.37	2.68	2.60
SEm±		0.27	0.27	0.31	0.46	0.89	0.87

§ - Between S_0 and levels of S; §§ - Between levels of S

Table 84. Rice yield and uptake of S as influenced by levels of sulphur applied as ^{35}S

Treatment		Rice cultured in brown hydromorphic soil					
		Grain yield ($g\ pot^{-1}$)	Straw yield ($g\ pot^{-1}$)	Total drymatter ($mg\ pot^{-1}$)	Total grain S ($mg\ pot^{-1}$)	Total straw S ($mg\ pot^{-1}$)	Total S uptake ($mg\ pot^{-1}$)
Source of Sulphur	AS	9.68	13.81	23.55	12.99	19.39	32.24
	APS	10.38	14.48	24.87	15.38	21.80	37.18
LSD at 5%		0.33	0.58	0.72	0.93	1.65	2.09
SEm±		0.11	0.19	0.24	0.31	0.55	0.69
Control	S_0	8.87	11.50	20.27	7.99	9.08	17.07
^{35}S levels ($kg\ ha^{-1}$)	S_{10}	9.38	13.32	22.70	10.49	15.86	26.06
	S_{20}	10.13	14.08	24.28	13.81	18.88	32.70
	S_{30}	10.48	14.43	24.92	15.95	22.55	38.51
	S_{40}	10.13	14.75	24.93	16.48	25.08	41.56
LSD at 5%§		0.56	1.00	1.25	1.62	2.85	3.62
LSD at 5%§§		0.46	0.82	1.02	1.32	2.33	2.96
SEm±		0.15	0.27	0.34	0.44	0.78	0.98
Control	S_0	8.87	11.50	20.27	7.99	9.08	17.07
Source-1 (AS)	S_{10}	9.26	13.10	22.36	10.34	15.68	25.42
	S_{20}	9.96	13.70	23.80	13.29	17.50	30.79
	S_{30}	10.00	14.17	24.16	13.96	21.48	35.44
	S_{40}	9.50	14.27	23.86	14.37	22.91	37.29
Source-2 (APS)	S_{10}	9.50	13.53	23.03	10.65	16.05	26.70
	S_{20}	10.30	4.47	24.76	13.81	20.27	34.61
	S_{30}	10.96	14.70	25.66	15.95	23.62	41.57
	S_{40}	10.76	15.23	26.00	16.48	27.24	45.84
LSD at 5%		0.65	1.16	1.44	1.87	3.30	4.18
SEm±		0.22	0.39	0.48	0.62	1.10	1.39

§ - Between S_0 and levels of S; §§ - Between levels of S

Table 85. Rice yield and uptake of S as influenced by two types of soils (Pooled analysis)

Treatment		Grain yield (g pot^{-1})	Straw yield (g pot^{-1})	Total drymatter (g pot^{-1})	Total grain S (mg pot^{-1})	Total straw S (mg pot^{-1})	Total S uptake (mg pot^{-1})
Source of Sulphur	AS	9.16	13.24	22.38	11.89	18.05	29.87
	ASP	9.36	13.64	23.00	13.55	20.24	33.82
LSD at 5%		NS	0.39	0.61	0.79	1.06	1.25
SEm±		0.14	0.13	0.20	0.26	0.35	0.42
Control	S_0	8.08	11.10	18.82	6.61	8.50	15.11
^{35}S levels (kg ha^{-1})	S_{10}	8.78	12.76	21.43	9.63	14.86	24.34
	S_{20}	9.46	13.44	22.94	12.49	17.59	30.08
	S_{30}	9.67	13.77	23.43	14.40	20.97	35.44
	S_{40}	9.12	13.81	22.95	14.37	23.17	37.54
LSD at 5%§		0.71	0.67	1.05	1.38	1.85	2.16
LSD at 5%§§		0.58	0.55	0.86	1.13	1.51	1.77
SEm±		0.20	0.18	0.29	0.37	0.50	0.59
Control	S_0	8.08	11.10	18.82	6.61	8.50	15.11
Source-1 (AS)	S_{10}	8.82	12.68	21.27	9.73	14.52	23.95
	S_{20}	9.42	13.23	22.72	12.14	16.48	28.62
	S_{30}	9.45	13.57	23.02	12.90	19.92	32.82
	S_{40}	8.96	13.50	22.52	12.82	21.29	34.11
Source-2 (APS)	S_{10}	8.75	12.85	21.60	9.54	15.19	24.73
	S_{20}	9.52	13.65	23.17	12.85	18.69	31.55
	S_{30}	9.88	13.97	23.85	15.89	20.03	38.06
	S_{40}	9.28	14.12	23.40	15.91	25.05	40.96
LSD at 5%		0.83	0.78	1.23	1.59	2.13	2.51
SEm±		0.28	0.26	0.41	0.53	0.71	0.84
Alluvial		8.48	12.74	21.17	11.26	17.69	28.99
Brown hydromorphic		10.03	14.14	24.21	14.18	20.59	34.71
LSD at 5%		0.42	0.39	0.61	0.79	1.07	1.25
SEm±		0.14	0.13	0.20	0.26	0.36	0.42

§ - Between S_0 and level of S; §§ - Between levels of S

The grain yield, straw yield, total drymatter, total grain sulphur, total straw sulphur and total uptake of sulphur were increased by higher levels of sulphur application.

The pooled analysis of results of data also showed that the grain yield, straw yield, total yield, total grain sulphur, total straw sulphur and total sulphur uptake were significantly more in brown hydromorphic soils compared to alluvial soil.

4.4.3 Sulphur use efficiency

The utilization of native and applied sulphur (^{35}S) is presented in Table 86 to 88. The Table 86 shows that in alluvial soil the sulphur derived from fertilizer (Sdff) sulphur derived from soil (Sdfs), A-value, sulphur use efficiency and sulphur in plant derived from fertilizer did not significantly vary due to source of sulphur.

The effect of sulphur levels showed that Sdff increased with higher levels of sulphur where as Sdfs decreased. A value was on par between levels. Sulphur use efficiency increased with levels and the highest level was at S_{20}. The sulphur use efficiency of S_{10}, S_{20} and S_{30} were on par; and S_{40} had the lowest S-use efficiency.

In brown hydromorphic soil significant difference between sources of sulphur was seen only in quantity of sulphur taken up from fertilizer, in which APS had a higher level of uptake of fertilizer applied.

Table 86. Utilisation of native and applied sulphur by rice (Alluvial soil)

Treatment		% Sdff	% Sdfs	A value (ppm)	Sulphur use efficiency (%)	S in plant taken up from fertilizer (mg pot^{-1})
Source of Sulphur	AS	44.21	55.87	14.59	20.87	12.52
	APS	41.22	58.78	16.42	21.48	13.08
LSD at 5%		NS	NS	NS	NS	NS
SEm±		1.35	1.33	0.81	0.86	0.50
^{35}S levels (kg ha^{-1})	S_{10}	25.08	75.25	15.77	22.21	5.59
	S_{20}	42.07	57.93	14.10	23.15	11.58
	S_{30}	49.37	50.62	15.69	21.25	15.94
	S_{40}	54.51	45.49	16.46	18.11	18.10
LSD at 5%		5.78	5.72	NS	3.65	2.14
SEm±		1.91	1.88	1.15	1.22	0.71
Source-1 (AS)	S_{01}	24.42	75.58	15.55	21.98	5.49
	S_{20}	44.52	55.48	12.80	23.61	11.80
	S_{30}	50.67	49.33	14.65	20.42	15.32
	S_{40}	56.88	43.12	15.37	17.48	17.47
Source-2 (APS)	S_{10}	25.06	74.93	15.99	22.43	5.69
	S_{20}	36.61	60.39	15.39	22.69	11.35
	S_{30}	48.07	51.93	16.72	22.08	16.56
	S_{40}	52.13	47.87	17.55	18.73	18.73
LSD at 5%		8.81	8.09	NS	5.17	3.02
SEm±		2.69	2.67	1.62	1.72	0.99

Table 87. Utilization of native and applied sulphur by rice (Brown hydromorphic soil)

Treatment		Rice cultivated in brown hydromorphic soil				
		% Sdff	% Sdfs	A value (ppm)	Sulphur use efficiency (%)	S in plant taken up from fertilizer (mg pot^{-1})
Source of Sulphur	AS	40.45	59.55	16.58	22.78	13.79
	APS	39.34	61.66	18.22	24.44	15.39
LSD at 5%		NS	NS	NS	NS	1.34
SEm±		0.85	1.07	0.81	0.88	0.44
^{35}S levels (kg ha^{-1})	S_{10}	22.56	77.44	17.83	23.67	5.86
	S_{20}	35.76	64.24	17.38	24.17	12.08
	S_{30}	47.89	52.10	16.87	24.51	18.38
	S_{40}	53.02	46.97	17.82	22.05	22.04
LSD at 5%		3.61	4.62	NS	NS	1.89
SEm±		1.19	1.52	1.14	1.25	0.62
Source-1 (AS)	S_{10}	23.69	76.31	16.75	24.25	6.06
	S_{20}	35.31	64.69	16.55	23.50	11.75
	S_{30}	50.10	49.89	14.95	23.65	17.74
	S_{40}	52.70	47.30	18.06	19.61	19.61
Source-2 (APS)	S_{10}	21.43	78.57	18.91	23.09	5.66
	S_{20}	36.21	63.79	18.20	24.84	12.42
	S_{30}	45.69	54.31	18.18	25.37	19.02
	S_{40}	53.35	46.65	17.58	24.48	24.48
LSD at 5%		5.12	6.53	NS	NS	2.67
SEm±		1.69	2.15	1.62	1.76	0.88

The effect of levels showed that Sdff increased with higher levels of sulphur. A-value and sulphur use efficiency were on par. Sulphur in plant taken up from fertilizer showed significant increase with sulphur levels.

Table 88 shows the pool analysis of two soil types. It is seen the A-value by APS source increased over that by AS. The Sdff due to higher levels of sulphur increased where as the Sdfs decreased. A value for all levels were on par. Sulphur use efficiency of S_{10}, S_{20} and S_{30} were on par. But the higher level S (S_{40}) decreased the sulphur use efficiency. Highest value of S-use efficiency was seen for the level S_{20}. Sulphur in plant taken up fertilizer increased with levels of S.

The Sdff in alluvial soil was significantly high, where as Sdfs and A-value were low. The utilization of applied sulphur and quantity of sulphur taken up fertilizer were high for brown hydromorphic soil.

Table 88. Effect of soil on the utilization of applied (^{35}S) and native sulphur (pooled analysis)

Treatment		% Sdff	% Sdfs	A value (ppm)	Sulphur use efficiency (%)	S in plant taken up from fertilizer (mg pot^{-1})
Source of Sulphur	AS	42.39	57.71	15.58	21.81	13.16
	APS	40.24	59.76	17.32	22.96	14.24
LSD at 5%		NS	NS	1.67	NS	0.94
SEm±		0.79	0.81	0.56	0.58	0.31
^{35}S levels (kg ha^{-1})	S_{10}	23.78	76.22	16.79	22.94	5.73
	S_{20}	38.91	61.08	15.74	23.66	11.83
	S_{30}	48.63	51.36	16.12	22.88	17.16
	S_{40}	53.76	46.24	17.14	20.07	20.07
LSD at 5%		3.37	3.65	NS	2.43	1.33
SEm±		1.12	1.22	0.79	0.81	0.44
Source-1 (AS)	S_{10}	24.14	75.86	16.15	23.12	5.78
	S_{20}	39.92	60.08	14.68	23.55	11.77
	S_{30}	50.39	49.61	14.80	22.04	16.53
	S_{40}	54.79	45.21	16.71	18.55	18.54
Source-2 (APS)	S_{10}	23.42	76.58	17.45	22.76	5.67
	S_{20}	37.91	62.09	16.80	23.77	11.88
	S_{30}	46.88	53.12	17.45	23.72	17.79
	S_{40}	52.74	47.26	17.57	21.60	21.60
LSD at 5%		4.77	5.17	NS	3.44	1.88
SEm±		1.59	1.72	1.12	1.15	0.63
Alluvial		42.75	57.25	15.50	21.18	12.80
Brown hydromorphic		39.79	60.21	17.39	23.59	14.59
LSD at %		2.38	2.58	1.67	1.72	0.94
SEm±		0.79	0.86	0.56	0.57	0.31

Discussion

5. DISCUSSION

A series of investigations were conducted at College of Horticulture, Kerala Agricultural University, Vellanikkara during 1990-1994 entitled "Status and availability of sulphur in the major paddy soils of Kerala and the response of rice to sulphatic fertilizers". To achieve the objectives of the study, the investigations were divided in to four parts and the results obtained are discussed hereunder.

5.1 Part-I. Assessment of the sulphur status of rice soils of Kerala

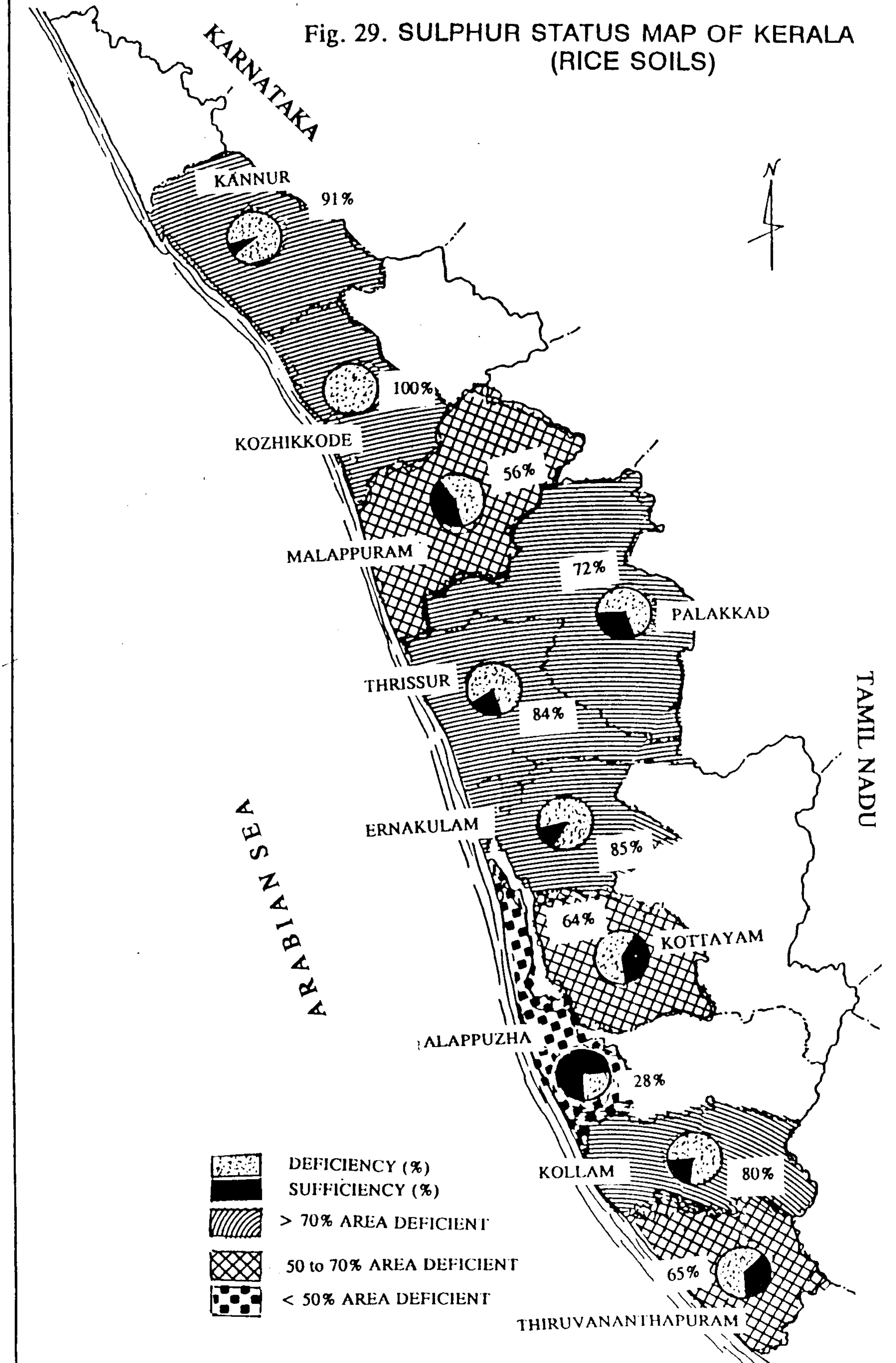
The aim of this part of the study was to assess the sulphur status of major paddy soils of Kerala. The rice soils of Kerala are mainly of two types viz. alluvium and colluvium and are grouped as alluvial soils and brown hydromorphic soils (Anon, 1978). The study was conducted in these two types of soils falling in the stretch of rice area of 10 major rice growing districts of the State. The grouping in to alluvial and brown hydromorphic soil was done based on the type of soil (Gopalaswamy, 1983 and Anon, 1984) to which it fell, and in consultation with the experts in Soil Survey Department. Two hundred and ten soil samples @ 105 from each soil type belonging to 10 districts based on the area under rice (Anon, 1989) were collected and analysed for soluble SO_4-S, adsorbed sulphate and total sulphur. From this the fractions of organic + nonsulphate sulphur were estimated. In this study to estimate adsorbed SO_4-S and organic sulphur the procedures suggested by Fox *et al.* (1959) and Singh *et al.* (1993) were followed. Phosphate ion is most widely used to displace adsorbed sulphate and potassium dihydrogen orthophosphate has usually been used to extract adsorbed sulphate (Barrow, 1967). Adsorbed sulphate was estimated by deducting calcium chloride extractable sulphur from phosphate extractable sulphur. Organic sulphur is the difference between total sulphur and phosphate extractable sulphur (Fox *et al.*, 1964).

Based on the available sulphur content classification of samples in to low, medium and high was done as per the standard procedures (Govindarajan and Rao, 1978 and Arora and Takkar, 1988).

The study revealed that 56 per cent under alluvial soils and 83 per cent under brown hydromorphic soils were deficient in available sulphur as extracted by $CaCl_2$. In Palakkad district from where 29 soil samples were analysed from riverine alluvium , 19 samples fell in deficient level (< 10 ppm). In Alappuzha district out of 19 samples analysed, only 3 soil samples came under deficient level which constituted 45 per cent of total sulphur under high category. The reason for such high percentage of sulphur rich soils in that district is the inclusion of Karappadam rice fields which is riverine alluvium formed in the river basin of Pamba river. These soils contained high organic carbon and high sulphur content (Appendix IIa). At the same time the sandy soil with low organic matter content in Onattukara region which belonged to coastal alluvium, and greyish Onattukara were low in SO_4-S content. In Kollam district where alluvial rice soils samples belonged to coastal alluvium (Karunagapally Taluk) all the samples showed deficient level of sulphur. This low soil sulphur status in coastal alluvium is due to poor fertility (Anon, 1984).

In brown hydromorphic soils 83 per cent of the soil samples fell in deficient category. Compared to alluvial soil high S category were less in brown hydromorphic soil. The hydromorphic soils contain high level of iron in their profile (Moorman and Van, 1978 and Stoops and Eswaran, 1985). Sulphur deficiency is

Fig. 29. SULPHUR STATUS MAP OF KERALA (RICE SOILS)



associated with high level of Fe in flooded soils (Ponnamperuma, 1985). Taking 15 ppm as critical limit for available sulphur Ayyappan *et al.* (1989) observed that 47 per cent of the soils belonging to coffee grown zone in Karnataka were delineated as deficient. In Alfisols and Vertisols of Karnataka the variability between different forms of sulphur showed a range of 1.4 to 3500 ppm and extractable sulphur was only 2.5 per cent of the total sulphur (Balanagoudar and Sathyanarayana (1990). Taking 10 ppm as critical level they found that 51 per cent soils were deficient in sulphur. Adsorbed SO_4 concentrations were strongly correlated with iron and aluminium (Neary *et al.*, 1987).

The experiment to study the sulphur status made it possible to delineate sulphur deficiency level in each district. This study has given a clearer picture of S status of rice soils of Kerala in the light of the report of Tandon (1988 and 1991), that soils in all districts of Kerala are deficient in sulphur.

Sulphur status map of rice soils, in Kerala prepared on the basis of analytical data shows a clear depiction of the gravity of deficiency of sulphur in 90 per cent of rice soils of the state studied in this investigation. In Kerala, rice is cultivated mostly as a monocrop. The introduction of rock phosphate as an economical phosphatic fertilizer in acid soils, switching over to high yielding varieties, reduction in the use of farm yard manure for rice (Kanwar, 1976), leaching due to high rainfall, and high content of iron in soils which render the soluble forms of sulphur to insoluble or adsorbed forms, could be assumed as some of the reasons for the deficiency of sulphur in rice fields of Kerala.

The table on ranges and means showed that the rice soils in Kerala had both extremes of sufficiency and deficiency. The mean values of soluble sulphate

Plate 1. General view of pot culture conducted in Part II of the investigations to determine the critical levels of sulphur

Plate 2. A close view of the pots which show the accumulation of green algae in control (-S) compared to sulphur applied (+S)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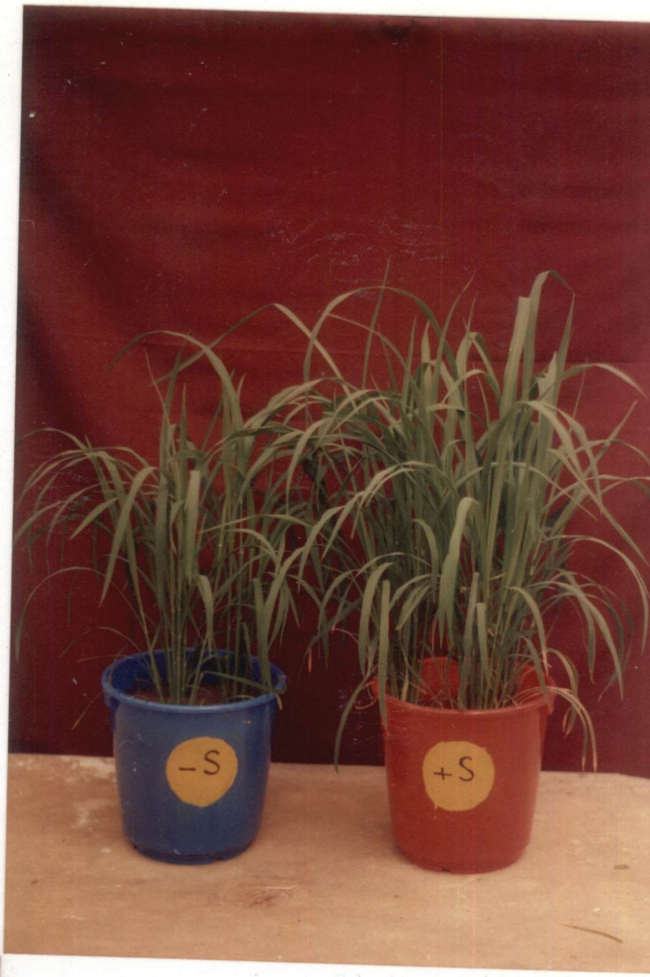
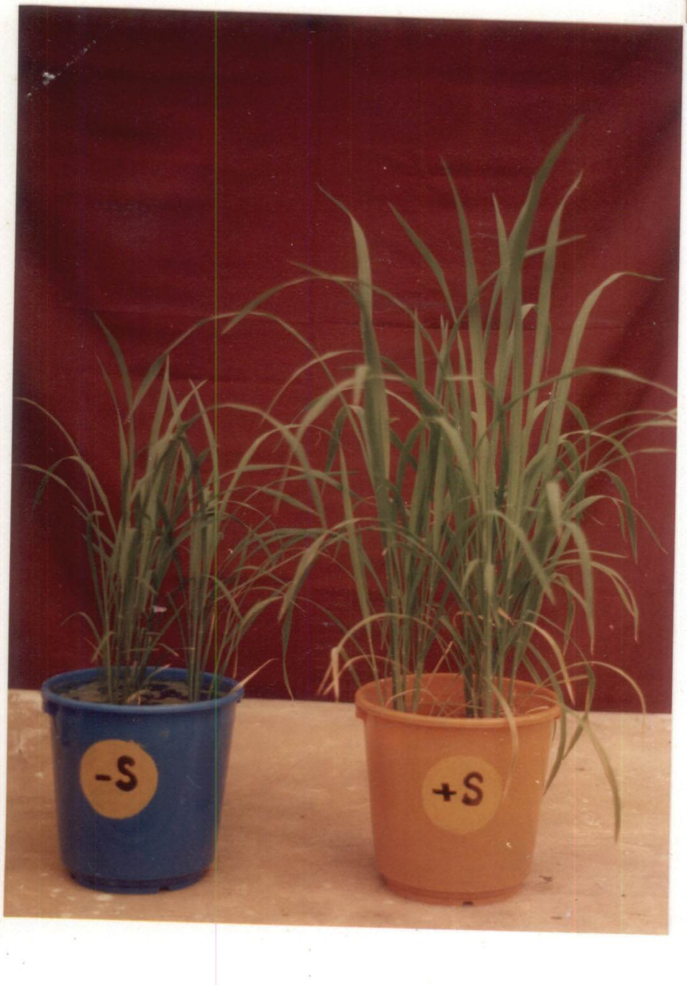
-S
+S

Plate 3. Rice growth in alluvial soil under sulphur application and control

Plate 4. Rice growth in brown hydromorphic soil under sulphur application and control


–S
+S

-S
+S

sulphur, adsorbed sulphate, organic sulphur and total sulphur of alluvial and brown hydromorphic soils showed that the mean values concentrated towards the lower values of the respective ranges. This indicated that more samples were in the lower sulphur category. A similar trend was seen in the findings of Karwasra *et al.* (1986). The correlation studies showed that pH had a significant negative correlation with all forms of sulphate sulphur and organic carbon had a significant positive correlation. Karwasra *et al.* (1986), Balanagoudar and Sathyanarayana (1990a) and Kher and Singh (1993) reported similar correlation between pH and organic carbon with different fractions of sulphur in soils. The decrease in pH resulted in increased positive charges on the soil surface which would cause greater adsorption of sulphur as SO_4^{2-} ions (Hesse, 1971).

From this part of the study the alluvial and brown hydromorphic rice soils of different locations in 10 districts of Kerala could be delineated to areas of low, medium and high level of sulphur. Turbidimetric methods had been used for estimation of available sulphur status in the rice soils of Kerala in Part I. This method had proven to be convenient and reproducible procedure for SO_4 analysis of a wide range of solutions including plant extracts (Lee and Wells, 1980 and Wall *et al.*, 1980) and soil extracts (Sinclair, 1973). The turbidimetric method is easier to operate, less expensive, and capable of analysing more samples per hour than other methods (Anderson *et al.*, 1992). However, the measurement of sulphur varied based on type of extractant and pretreatments operating conditions and type of soils. Therefore, it was necessary to find out the critical level for each extractant to meaningfully interpret the analytical data for estimation of sulphur. Hence further investigations on critical levels under different methods of estimation of sulphur status was followed up in Part II.

5.2 Part-II. Identification of suita ? soil test procedure for estimation of available sulphur

The objectives of this part of the investigation were (1) to evaluate the critical levels of sulphur in alluvial and brown hydromorphic soils under different procedures of S estimation and (2) to identify a most suitable method of soil analysis for sulphur estimation in these two types of soils.

To achieve these objectives 30 soils each from alluvial and brown hydromorphic types were selected representing low, medium and high categories as delineated in Part I and as such a pot culture trial was conducted at Radiotracer Laboratory, Kerala Agricultural University, Vellanikkara, during 1991-92. These soils were analysed for their available sulphur content using 12 extractants as outlined under materials and methods. The analysis was modified (Freney, 1958) standardised the time of extraction as 30 minutes and replicated 4 times. The data on available sulphur extracted by different procedures and relative grain yield, relative straw yield, relative total biomass and relative uptake of sulphur were plotted in scatter diagram and the critical levels estimated as suggested by Cate and Nelson (1965 and 1971). In alluvial soils among the different procedures studied extraction with monocalcium phosphate (500 ppm P) significantly and positively correlated with most other extractants.

Among the extractants ammonium acetate + acetic acid, Olsen's regent, monocalcium phosphate and calcium chloride were having high correlations with relative yields and relative uptake of S. The mean values for range and mean critical concentration in alluvial soil were 2.7 to 27.5 and 12.2 ppm. The critical concentration by four extractants viz. ammonium acetate + acetic acid, monocalcium phosphate, monocalcium phosphate + acetic acid, and potassium dihydrogen orthophosphate had 15 ppm as their critical value for sulphur extraction. The lowest critical value was for water (5 ppm) and highest critical concentration was for Olsen's reagent (22 ppm). The responsiveness and non responsiveness of soils at 40 kg S ha^{-1} and the increase or decrease of grain yield (Table 13) pointed towards monocalcium phosphate as the best extractant for alluvial soil. Monocalcium phosphate grouped of 15 soils, from among the 30, as non responsive and they were really non responsive as they decreased the yield under S application by the minimum value of 0.1 per cent.

In brown hydromorphic soils, potassium dihydrogen orthophosphate had high correlations with most other extractants. Ammonium acetate + acetic acid had the highest correlation with relative yields. The lowest critical concentration has for water (6 ppm) and the highest is for Olsen's reagent (20 ppm). Further tabulation on the identification of responsive and non responsive soil and grouping them from among 30 soils (Table 19) showed that monocalcium phosphate + acetic acid was the best among the extractants which could group the non responsive soils more effectively with the lowest increase in grain yield under S application. This was followed by other extractants in the order monocalcium phosphate, Morgan's extractant and calcium chloride.

In alluvial and brown hydromorphic soils, water extracted sulphur with critical levels of 7 and 6 ppm respectively. Water is the simplest extractant for sulphate sulphur. But it had two disadvantages. In the first case water usually deflocculates the soil, thus making the extract difficult to filter. Secondly water extracts sulphur which is not available to plants or micro organisms (Barrow, 1967).

Higher concentrations of total extractable sulphur removed by water could not be accounted for any increases in the sulphate sulphur concentration but was the result of dispersion of the organic material and therefore more organic matter was probably extracted in the water than in the weak salt extractants (Maynard *et al.*, 1987). Similar results were also reported by Islam and Buiyan (1988) and Blair *et al.* (1991). Monocalcium phosphate was found to be the best extractant for alluvial soil. In alluvial soils next to monocalcium phosphate, ammonium acetate + acetic acid was found to be the good extractant for sulphur extraction since it identified and grouped soils of deficiency accurately, where there was only 0.76 per cent increase in yield by non responsive soils. Palaskar and Ghosh (1982) extracted available sulphur in alluvial soil and observed significant positive correlation of extracted S with drymatter yield and sulphur uptake. Similar findings were also reported by Bansal *et al.* (1983) and Tiwari *et al.* (1993).

Phosphate would replace and or reduce the adsorption of sulphate. The strength of retention of anions by soils follows the order: phosphate > sulphate = acetate > nitrate = chloride. There is little effect of chloride on sulphate retention (Walsh and Beaton, 1973). Monocalcium phosphate is easy to prepare and it is easy to filter. It is effective since it removed all the sulphur which is available to plants without removing that which was not available (Barrow, 1967).

In brown hydromorphic soils the best extractant suitable was found to be monocalcium phosphate + acetic acid. It showed that comparatively a more acidic extractant was found best for brown hydromorphic soil. In this connection it is to be recalled that the mean pH of 30 samples of brown hydromorphic soil was less acidic (pH 5.58) compared to the alluvial soils of which the mean pH was low (pH 5.00).

The suitability of $Ca(H_2PO_4)_2$ + HOAc as a good extractant had been already reported by Spencer (1979), Palaskar and Ghosh (1982) and Islam and Buiyan (1988). According to Barrow (1967) though monocalcium phosphate is a good extractant it does not mean that all the sulphate extracted by monocalcium phosphate may be readily taken up by plants especially where affinity of the soil for sulphate is high, reaction between sulphate and soil may slow diffusion to the roots.

Phosphate solution extract higher levels of S than either H_2O or Cl salt solutions. However, this difference is usually significant in low adsorbing soils (Anderson *et al.*, 1992). The above report is corroborative to the findings in this study where, the low S containing soils showed not much variation between S extracted by phosphates and chlorides (Table 8 and 14).

In this study it was seen that Olson's reagent extracted the highest level of sulphur from soil. Anderson *et al.* (1992) reported that the alkalinity of the $NaHCO_3$ solution was the agent responsible for hydrolysing the soil organic S. Kilmer and Nearpass (1960) found that at a higher pH more soil organic sulphur was extracted. It was reported that $NaHCO_3$ method extracted S from both adsorbed sulphate and a fraction of the soil organic sulphur and the level of S extracted was 1.1 to 5.6 times greater than the amount extracted by the phosphate solutions (Anderson *et al.*, 1992, Probert, 1976 and Rehm and Caldwell, 1968).

From the discussion of the results of Part II of the study it could be inferred that monocalcium phosphate (500 ppm P) is the best extractant for alluvial soils. Ammonium acetate + acetic acid is the next best extractant and 15 ppm S is the critical level under both the extractants. For brown hydromorphic soils monocalcium phosphate + acetic acid is the best extractant followed by monocalcium phosphate. The critical level for these two extractants are 10 ppm and 17 ppm respectively.

The modifications adopted in the procedures for accuracy of estimation were -

(i) The sensitivity of concentrations was increased by maintaining a constant level of sulphur in the reading solution (5 ppm) since many samples contained low level of sulphur (Frency, 1958 and Massoumi and Cornfield, 1963).

(ii) 1 scoop (approx. 2 g) activated charcoal was added to the extractants, shaken for 30 minutes and filtered to remove organic matter (Fox *et al.*, 1964 and Hoeft *et al.*, 1973).

Correlations between green algae, soil SO_4-S, grain yield, relative biomass yield, sulphur content of grain and straw showed green algae had significant negative correlation with relative yield, S content of plant parts and soil S. It indicated that the green algae was more in sulphur deficient soil. Sulphur application is an effective measure to control green algae which is a weed in rice fields. It is discussed in detail under Part III. The grain yield was not significantly correlated with green algae as the grain yield was indipendant of sulphur application (since it related to S_0 pots).

It was seen that the critical content of sulphur in straw at maturity in the rice plants grown in alluvial soil was 0.075 per cent. The same in brown hydromorphic soil is 0.08 per cent (Fig.28). Plant composition is used as a method to assess sulphur deficiency (Freney *et al.*, 1962). Eaton (1975) classified the tissue analysis values useful in indicating sulphur status, and propounded that, at the concentration of 0.053 to 0.062 per cent S in rice straw, the plant would have poor growth or show deficiency symptoms and the intermediate range between deficiency and sufficiency is 0.100 to 0.118 per cent. Based on the above rating of Eaton (1975) the critical levels now estimated in both the soils can be taken as a good criteria to identify deficiency in alluvial and brown hydromorphic rice fields of Kerala.

5.3 Part-III. Response of rice to levels and sources of sulphur

Response of rice to the common fertilizers may not always be due to their nitrogen or phosphorus alone but also to the sulphur they contain, and therefore in basic studies of fertilizer requirements, it is desirable to regard sulphur as a major nutrient and to arrange for its observation separately from nitrogen phosphorus or potassium (Grist, 1975). This part of the study was aimed to assess the response of rice to two popular sulphatic fertilizers of Kerala, viz., ammonium sulphate and ammonium phosphate sulphate. The location for conducting this experiment was selected from the soils used for Part II based on the available sulphur status. Cropping Systems Research Centre, Karamana in Thruvananthapuram district belongs to alluvial type having available sulphur status of 6.4 ppm S and Regional Agricultural Research Station, Pattambi in Palakkad District belongs to brown hydromorphic type having pH of 9.6 ppm were selected for conducting field experiments for two seasons (*Kharif* and *Rabi*) during 1992-93 simultaneously. These two locations are situated about 350 km apart towards south and north respectively of pot culture location. The results of field experiments are discussed hereunder. The general view of field experiment is presented by Plates 5 and 6.

Height of plants, generally, increased by APS over that by AS. The sulphur levels also progressively and significantly increased the height of plants. Leaf area index at different stages showed that sulphur levels progressively and significantly increased leaf area index. Number of tillers per hill at maturity increased due to APS in *Kharif* season on both locations. The sulphur levels significantly increased the number of tillers progressively upto S_{30}. In general there was significant and progressive increase in the growth of plant from control to S_{30} as per graded levels of S. The effect of sulphur on plant growth is well studied and established.

A deficiency of sulphur in rice makes it chlorotic at tillering; the plant is reduced both in height and number of tillers (Suzuki, 1978). The deficiency has a pronounced effect on plant growth characterized by stunted, thin stemmed and spindly plants (Tisdale *et al.*, 1985). Tokunaga and Tokuoka (1957) found that sulphur application increased growth, number of leaves and yield of rice. In Soil containing 33 ppm S, Karim and Khan (1958) observed increase in height, LAI, tiller number and yield upto 28 kg S ha^{-1}. Leaf area was much reduced and plants became shorter and thinner under S deficiency (Howard *et al.*, 1962). In the case of rice plants, it is most difficult to distinguish between sulphur and nitrogen deficiencies because they closely resembled each other in appearance (Suzuki, 1978). As in the case of nitrogen sulphur deficiency results in reduced plant height and tiller number and thin straw (Blair *et al.*, 1978). Nanawati *et al.* (1973) observed that content of chlorophyll, water soluble protein and peroxidase in rice were significantly reduced under conditions of sulphur deficiency. The reduction in water soluble protein is the result of lower synthesis of the sulphur containing amino acids, cystine, cysteine and

Plate 5. A view of field experiment conducted during *Kharif* season in brown hydromorphic soil to study the response of rice to sulphur

Plate 6. A view of field experiment conducted during *Rabi* season at RARS, Pattambi to study the response of rice to sulphur


RESPONSE OF RICE TO
SULPHATIC FERTILIZERS

Plate 7. Rice crop of control plot (T_1) showing errect earheads with less spikelets

Plate 8. Rice crop applied with APS @ 30 kg S ha^{-1} (T_8) showing drooping earheads with higher density of spikelets


R 1
T_1


R 1
T_8

methionine, which form an integral part of structural and functional protein (Mertz *et al.*, 1952). The above reports showed that the increases in height of plants, number of productive tillers and leaf area index with increased supply and availability of sulphur were due to the influence of sulphur in the structural protein and chlorophyll of rice plant.

George (1989) observed that at graded levels of sulphur the leaf area index increased in rice variety *Jaya* in experiments conducted at Mannuthy. Muraleedharan and Jose (1993) observed that in variety *Jyothi* applications of 10 kg S ha^{-1} during second crop season (*Rabi*) increased number of tillers and height in cm from 7.1 and 62.47 to 6.1 and 58.03 respectively of control plot.

Yield of rice was increased by the source APS over that by AS in all the four trials, similarly sulphur application increased grain yield over control and the lowest level of 10 kg S ha^{-1}. Straw yield was not affected by source. However, application of sulphur increased straw yield progressively upto S_{40}. In rice an increase in grain yield or straw yield is a manifestation of cumulative effect of contributions by yield attributes like number of productive tillers per square metre, number of grains per earhead, weight of grains etc. Plates 7 and 8 shows the comparative stand of rice in brown hydromorphic under control sulphur nutrition @ 30 kg S ha^{-1} (APS). Grist (1975) reported that application of 11 kg S ha^{-1} as sulphur containing fertilizers or inorganic materials can correct sulphur deficiency in rice but farm yard manure will not supply the necessary quantity of sulphur. When the addition of organic matter depress the plant growth it may be rectified by addition of sulphate (Nearpass and Clark, 1960). In Rice Research Station, Aduthurai (TNAU) a two years' field experiment with 100 kg ammonium sulphate ha^{-1} increased the yield of grain to 6136 kg from 3742 for control. When the sulphur levels increased with AS + Gypsum to 154 kg S ha^{-1} the yield increased further to 7117 kg (Ramanathan and Saravanan, 1985). Similarly Alam *et al.* (1985) who studied the effect of different sources of S on grain and straw at two locations found that ammonium sulphate increased both grain and straw yields on both the locations over elemental sulphur, gypsum and sulphur coated urea. In a similar experiment Singh and Chibba (1991) reported that ammonium sulphate @ 20 ppm increased the yield in maize and wheat when compared to the same level of S by the sources superphosphate, gypsum, elemental sulphur and pyrite. Increases in yield by ammonium sulphate source of S over other sources such as gypsum and elemental S has been reported by Prasad (1991) and Mamaril *et al.* (1991). Clarson and Ramaswamy (1992) reported that yield of grain was significantly high for APS source in rice varieties IR 50 and IR 62. On contrary to this, they found that the straw yield by AS source of S was higher compared to that by APS. This finding is corroborative to the result obtained in the present study that APS had significant effect on grain yield which did not reflect in straw yield. With regard to the effect of sulphur on grain yield they observed that the grain yields of IR 50 by 37.5 kg S ha^{-1} in form of AS and APS were 5860 and 5950 kg ha^{-1} respectively compared to 3116 kg ha^{-1} in control plot. Similar increases were also observed in IR 62 by application of sulphur over control. With regard to straw yield, application of sulphur increased straw yield over control in both IR 50 and IR 62. The findings of Clarson and Ramaswamy (1992) are in agreement with the results obtained in this experiment.

Increase in yield of rice by sulphur application upto 80 kg ha^{-1} has been reported by Blair *et al.* (1979). Beneficial effect of sulphur application in increasing rice yield has been reported by many workers (Ahmed *et al.*, 1989; Mukhi and

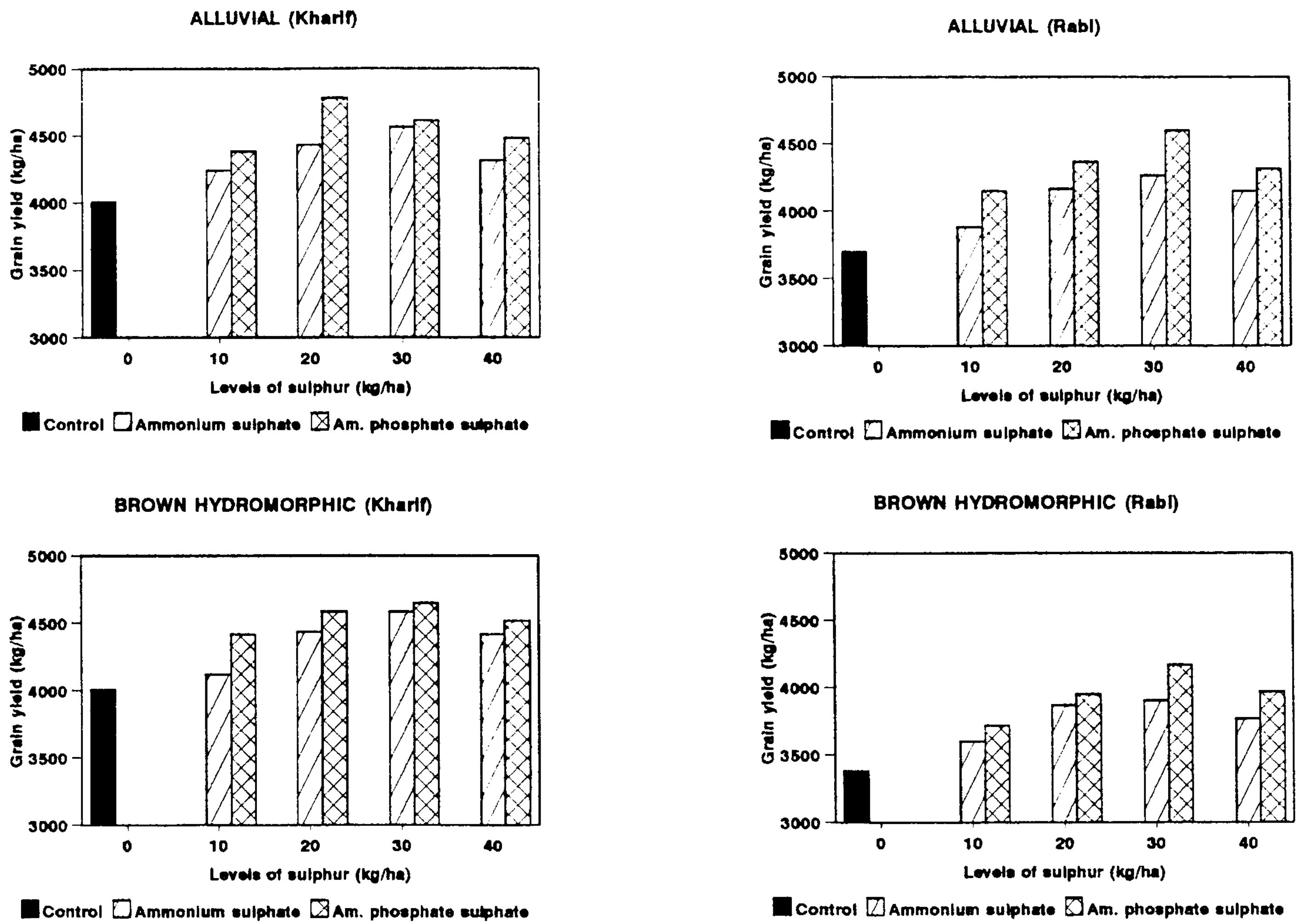


Fig. 30. **Grain yield (kg/ha) during Kharif and Rabi seasons in Alluvial and Brown hydromorphic soils as influenced by levels of sulphur**

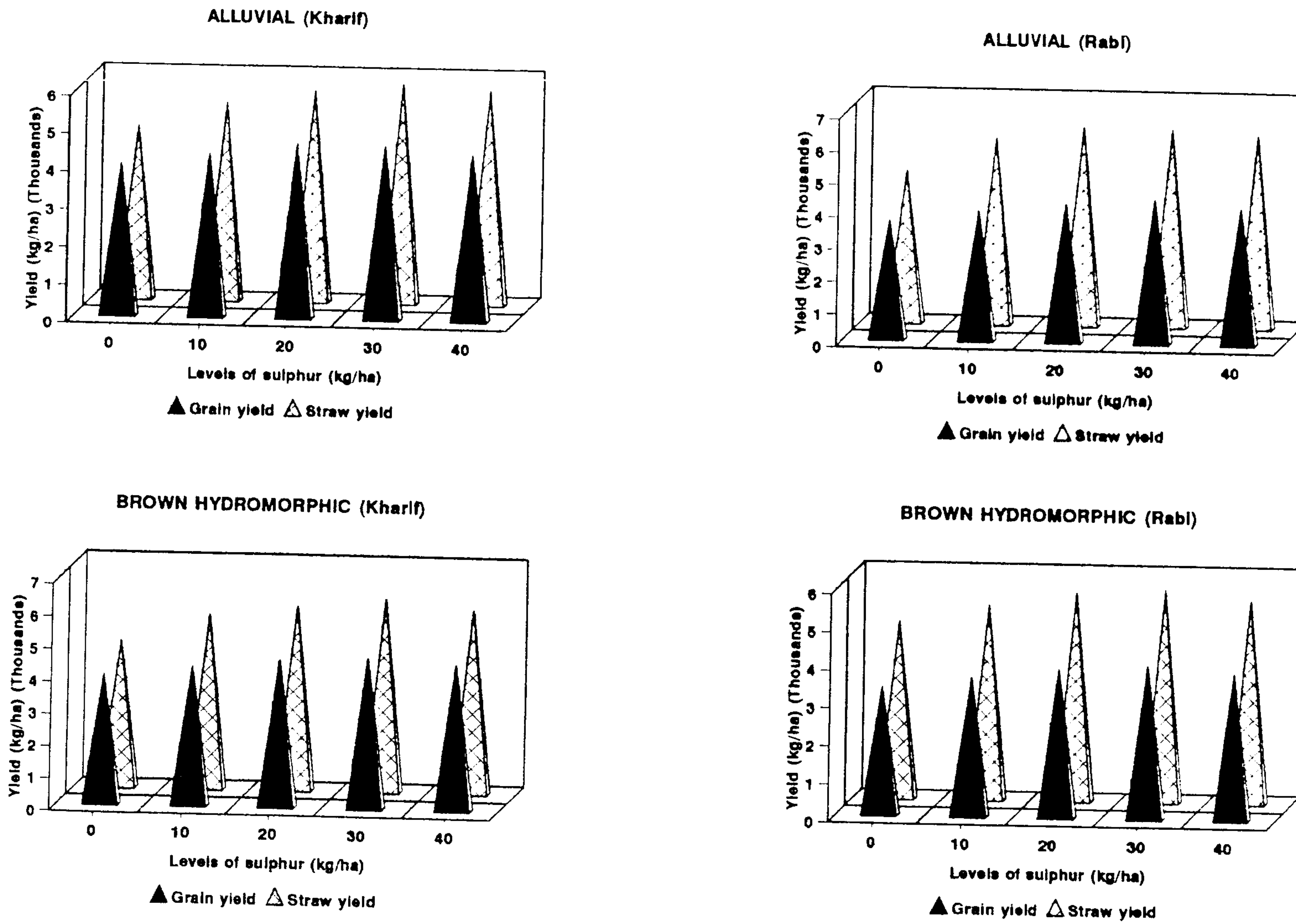


Fig. 31. **Relationship between yield of grain and yield of straw as influenced by levels of sulphur**

Shukla, 1991). The higher yield obtained during *Kharif* season can be attributed to the preceding fallow period, since, fallowing accelerates decomposition of soil organic matter and increases available sulphur resulting in higher plant growth on sulphur deficient soils (Howard *et al.*, 1962). Another reason for low yield of rice in *Rabi* season might be due to comparatively higher maximum temperature and lower minimum temperature (Fig.2) which might induced sterility of spikelets (Yoshida, 1981). Results of long term fertility experiments conducted at different centres in India during 1971-1983, compiled by Nambiar (1985), showed that average increase in rice grain yield, due to S incorporation, over optimum NPK input was 27 per cent. In the rice-rice cropping system at Bhubaneswar, 40 kg S ha^{-1} applied annually was found necessary to maintain optimum S level in the soil and sustain high productivity of the cropping system (De Datta *et al.*, 1990).

Number of productive tillers was significantly increased by APS over AS in alluvial soil. In both locations and seasons productive tillers increased by sulphur application. Number of grains per panicle and percentage of mature grains were significantly increased by sulphur levels. Weight of panicle and drymatter production were significantly higher with higher levels of sulphur. Sink capacity significantly increased with increase in sulphur application. The source-sink relationship as influenced by sulphur levels presented in the figures 30 and 31 showed that there was more or less perfect positive relationship between source and sink in both the soils. Here, the LAI at 60 DAT is taken as source as it is a good representative due to its direct involvement in the production of photosynthates (Venkateswarlu and Visparas, 1987). The linear and progressive relationship between the source and sink is an indication that what was produced by the source had efficiently stored in the sink in direct proportion. In other words the response of sulphur levels seen in the source

Fig. 32. Source-sink relationship in rice as influenced by sulphur levels (alluvial soil)

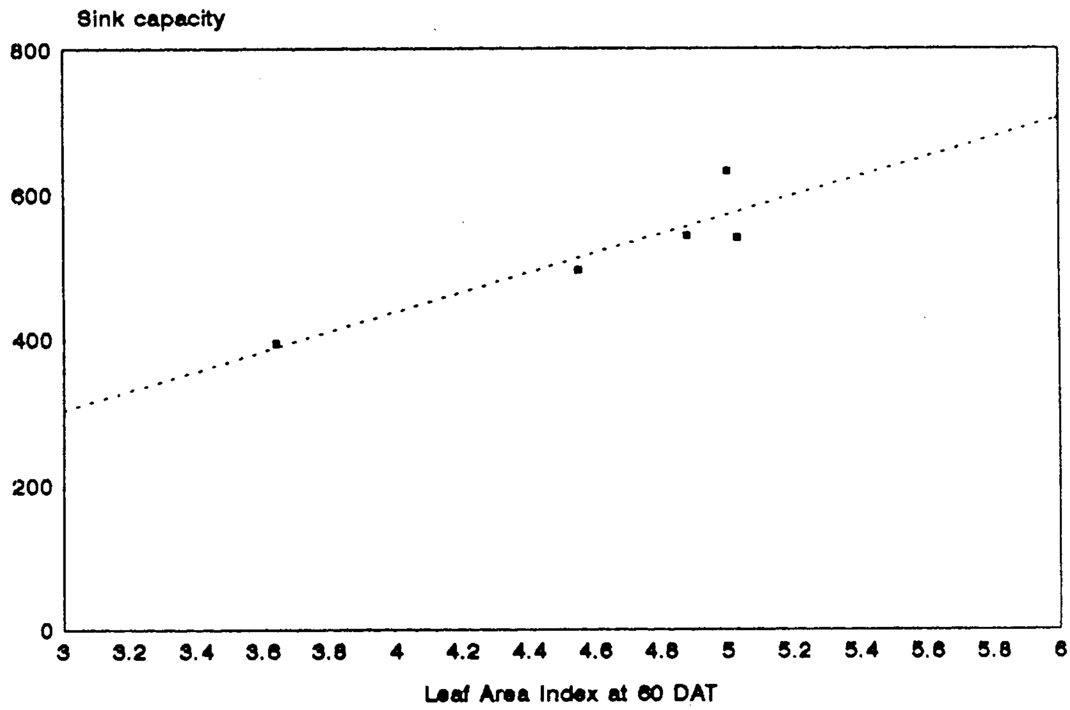
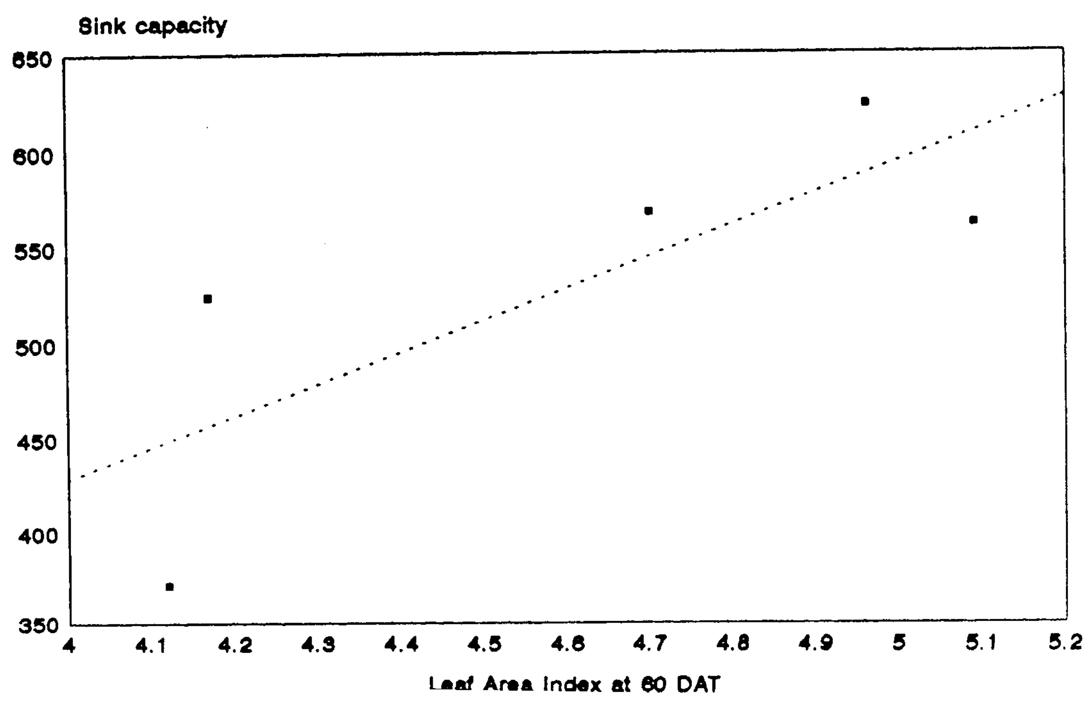


Fig. 33. Source-sink relationship in rice as influenced by sulphur levels (brown hydromorphic soil)



(LAI) is reflected as such in the sink (sink capacity) also. Sulphur nutrition studies have shown that while normal plants without sulphur deficiency produced 438 panicles per m^2, the stunted plants with S deficiency produced only 195 panicles per m^2 reducing it to less than 45 per cent (Wang, 1976). Sulphur deficiency reduced tiller number, delayed maturity, and increased the number of unfilled grains (Blair *et al.*, 1978). Blair *et al.* (1979) found that tiller number at active tillering, maximum tillering and maturity stages significantly and progressively increased upto 80 kg S ha^{-1} in flooded rice. They also observed that drymatter production at all the above three stages significantly and progressively increased upto 80 kg S ha^{-1}. In water culture with and without sulphur application Suzuki (1978) observed significantly higher number of tillers per hill, higher dry weight per hill, increased ear length and number of grains per ear and 1000 grain weight in rice. Ahmed *et al.* (1988) observed that tiller production in rice significantly increased with sulphur application upto 30 kg S ha^{-1} and there after the higher level of 60 kg S ha^{-1} decreased the number of productive tillers. Sulphur application increased the filled grain per panicle and percentage of filled grain (Ahmed *et al.*, 1989). However, it was also found that both 1000 grain weight and grain:straw ratio did not differ significantly. The harvest index was generally higher for control plots and it might be due to the low level of straw yield in control plots. However, the increase in harvest index at S_{30} in alluvial soil during *Rabi* season might be due to the increase in grain yield coupled with low straw yield as is seen in Tables 25 and 26. Muraleedharan and Jose (1993) reported that rice variety *Jyothi* gave a higher number of spikelets per panicle, and 1000 grain weight when applied with 10 kg ha^{-1} compared to control in two seasons of 1991 at Mannuthy, Kerala. Increases in number of panicle, number of grains per panicle, percentage of mature grains and weight of 1000 grains, progressively increased with increase in sulphur levels upto 20 kg S ha^{-1} have been reported by Ismunadji *et al.* (1987). However these parameters decreased with higher levels of S ha^{-1}. Ishizuka (1973) reported that 31 rice varieties of Far East recorded a wide variation of grain : straw ratio from 0.23 to 1.23. In the studies of George (1989) no significant variation in grain : straw ratio was observed in rice variety *Jaya* under higher levels of sulphur. The findings of the present study are corroborative to the findings of George (1989).

There was increase in gallfly incidence with sulphur application. This might be due to higher tiller production as is seen in Table 24. Green algae presence at brown hydromorphic soil showed that it decreased by APS and higher levels of sulphur. It is presumed that application of sulphur especially APS had some toxic property towards green algae. Green algae has been considered as a weed in wet land rice, where it is in abundance. Filamentous green algae develop in colonies in the surface soil after germination of spores. Gelatinous material around the algae filaments collects liberated gases in bubbles in the algae colonies. When sufficient gas thus accumulates, small sections of algae rise to the water surface where they continue to grow. Soon the gelatinous sections unite to form a solid mass of algae and the surface dries to rough film upon exposure to air. Young rice plants are pulled down in to the water or mud by the algae. Further new leaves and tillers cannot penetrate the algae (Smith Jr., 1967). The harmful effects of green algae as a weed in rice fields are most evident in the early stages of paddy growth; and cultural and mechanical means of algae control are not satisfactory, apart from it being expensive (Grist, 1975). Eventhough drawing copper sulphate @ 9 to 11 kg ha^{-1} in bags through the field is a recommended practice, copper resistance is reported in green algae (Mukherji, 1968). In the present study perfect control of green algae was seen with higher levels of sulphur. A similar decline in green algae growth was seen in pots supplied with 40 kg S ha^{-1} in pot culture under Part II. The harmful effect of green algae is usually not noticed as a serious problem by the farmers, as many see it as an inherent property of soil. But chemical control measures against green algae is recommended elsewhere (Mukherji and Sengupta, 1964; Smith, 1968). The present study shows that sulphur application, in addition to its role as a nutrient to rice for growth, controls the green algae effectively. Further it is evident, as is seen in Part II, that the S deficient locations can be identified by the presence of algal growth even when all the deficient fields do not show the presence of green algae.

It was seen that APS source and higher levels of sulphur significantly increased S content in grain and straw as well as total sulphur uptake. The uptake of sulphur increased with sulphur levels upto 40 kg S ha^{-1}. The quality of rice grain was found significantly influenced by application sulphur through AS or APS due to the increase in the protein, carbohydrate, cystine and methionine contents (Clarson *et al.*, 1991). Most of the sulphur contained in the plant and animal body occurs in proteins containing amino acids such as cystine, cysteine and methionine. Dietary sulphur requirement per kg of milk production is considered to be 1.33 g (Hasra, 1988). Since paddy straw is the main roughage for the cattle of Kerala an increase in S content in straw means an increase in quality of feed and ultimately an increase in milk production. The critical concentration of sulphur in plant at the time of harvest worked out in relation to grain yield as per Cate and Nelson method showed that the critical concentrations in alluvial soils was 0.075 per cent and in brown hydromorphic soils it was 0.08 per cent (Part II). In the field experiment it was observed that the sulphur content in straw of control plot plants recorded less than these critical levels in both the soil types. An application of 10 kg S in these two soils could correct this deficiency as seen in the study (Part IV). A glance to similar observations as shown below will confirm the findings of this experiment. Early studies by Ishizuka and Tanaka (1959) revealed that the critical concentration of S in straw appeared to be 0.068 per cent. According to Tanaka and Yoshida (1970) the critical content of S in straw at maturity was 0.067 per cent. Blair *et al.* (1978) reported that the content of S in whole plant tops at maturity of rice was 0.15 per cent. Osiname and Kang (1975) found that the critical content of S in grain and straw of rice were 0.12 and 0.1 per cent respectively. Yoshida *et al.* (1976) reported that the deficiency level (critical content) of S in straw at maturity was 0.1 per cent. It varied with stage of the crop and the critical content of S at tillering, flowering and harvest were found to be 0.16, 0.07 and 0.06 per cent respectively (Yoshida and Chaudhry, 1979). Yoshida and Chaudhry (1979) further reported that sulphur content in straw and grain were 0.041 and 0.058 respectively under 1 ppm level of sulphur where in, it increased to 0.121 and 0.084 respectively at 10 ppm S. Tiwari *et al.* (1983) observed that the critical contents of S in grain, straw and leaf blade at maturity were 0.095, 0.07 and 0.08 per cent respectively. In the present study it was observed that in control plots of all the four field experiments S content in straw was below 0.07 per cent and in S_{10} except in *Kharif* season in alluvial soils all the crops showed less than 0.1 per cent by 10 kg S ha^{-1}. This level as per the reports given above are below critical level. However the S content in straw at S_{30} and S_{40} were well within sufficiency level. The N:S ratio of rice straw varied widely (from 3 to 70) under varying N and S availability and N:S ratio in grain also varied from 15 to 56 (Yoshida and Chaudhry, 1979). Tiwari *et al.* (1983) observed that the N:S ratio at maturity corresponding to grain straw and leaf blade were 18, 13 and 15. In the variety IR 50 the N:S ratio of grain by APS and AS were 2.7 and 3.2 and in straw the same were 7.3 and 6.8 respectively (Clarson and Ramaswamy, 1992). In the present study the N:S ratio of grain and straw were found to have narrowed down to a level above the critical level as suggested by Yoshida and Chaudhry (1979). Wang (1976) reported that the rice variety *Apani* yielding 4.08 t grains removed 7.75 kg S ha^{-1} @ 1.9 kg t^{-1}. It was further observed that the removal of S was varying with variety; and variety *Peta* yielding 6.09 t grains removed 16.8 kg S ha^{-1} @ 2.28 kg t^{-1}. The uptake of S also varied widely with respect to application of sulphur. In severely S deficient soils sulphur application from 0 to 50 kg S ha^{-1} increased the uptake from 0.66 to 1.75 kg S t^{-1} (Wang, 1976). Manchanda *et al.* (1987) found that sulphur content in rice increased by 21 per cent to 43 per cent over control with sulphur application. A maximum of 0.094 per cent total S was recorded in plants supplied by 20 ppm S. Nambiar (1988) reported that the mean annual uptake through grain + straw by rice reduced from 11.5 to 4.8 kg S ha^{-1} in *Kharif* and 12 to 8.8 kg ha^{-1} in *Rabi* in sulphur applied and control plots respectively. In the present study the lowest uptake of S was observed during *Rabi* season in alluvial soil at S_0 (4.84 kg ha^{-1}) and the highest at S_{40} in *Kharif* at alluvial soils for S_{40} level as APS (14.87 kg ha^{-1}). The crop removal of S is a manifestation of the content of sulphur in plant parts extrapolated for the total yield obtained. Therefore, the increase in sulphur removal observed in the present study is a cumulative effect of increase in S content and total yield.

The content of nitrogen in grain and straw and the uptake of nitrogen was also seen to have increased by application of higher levels of sulphur. It was also seen that the source APS had favourable effect in content and uptake of nitrogen. The higher content of N is manifested in protein content also, since both are directly connected. Since nitrogen and sulphur are both closely linked in protein metabolism their relationship is reported to be synergistic (Hasra, 1988). There is a strong interaction of sulphur and nitrogen since it is seen that sulphur deficiency causes profound changes in the metabolism of plants with reduced protein synthesis and accumulation of soluble organic and inorganic nitrogenous compounds (Beaton, 1966). With increasing levels of applied S, the concentration of total N and protein N, increased but non protein N such as total soluble N, amide N and nitrate N decreased (Aulakh *et al.*, 1976). Studies at IRRI revealed that N content of straw at maturity increased from 0.54 per cent to 1.27 per cent when N and S application increased from 20 ppm and 1 ppm to 80 ppm and 10 ppm respectively (Yoshida and Chaudhry, 1979). Das and Datta (1973) reported from studies at the Nuclear Research Laboratory that protein content in rice grain increased from 7.93 per cent to 10.53 per cent when applied with 30 kg S ha^{-1} in the presence of 40 kg N ha^{-1}. They also observed that the increase in protein content was up to 12.22 per cent from 9.47 per cent when S @ 30 kg ha^{-1} was applied over control in the presence of higher levels of nitrogen. The increasing levels of sulphur concomitantly increased N content and significant interaction occurred between N and S in influencing nitrogen concentration in the plant tissue (Tiwari, 1990). Ismunadji and Miyake (1982) observed that application of S @ 0.5 g per pot increased the amino acid in brown rice to 28.0 per cent from 13.1 per cent in control plants. The unique role of sulphur in plant metabolism comes from its essential involvement in the synthesis of proteins within which the genetic information is embedded with (Lakhineni and Abrol, 1994). A deficiency of sulphur can cause an accumulation of non protein nitrogen in plants which can be detrimental to ruminant animals. If sulphur is limiting, nitrates accumulates in plant tissue. The nitrogen content in rice at deficient level of S may be at the expense of accumulation of non protein nitrogen which is elucidated in the findings of Yoshida and Chaudhry (1979) that reduction of S from 20 ppm to 0.1 ppm, at 80 ppm, nitrogen, resulted in increased N content in rice straw to 1.82 per cent due to accumulation of non protein nitrogen. Nitrate, in large quantities is toxic to animals (Tisdale *et al.*, 1985). In any areas where protein deficiency in human diets is a critical problem, plant products are the major foods consumed, since animal proteins contain more S amino acids. Since rice is the staple food of Keralites an increase in its nutritive value will have significant implication in the human nutrition and quality of animal feed also. The abundance of sulphur not only improves the protein content, but also improves the quality of produce by suppressing accumulation of toxic substances in plant such as selenium. Mikkelsen and Wan (1990) demonstrated from pot culture with rice plants that the presence of abundant SO_4 can ameliorate the phytotoxic effects of excess selenium, as plant Se concentrations decreased with SO_4 additions. Bansal (1992) found that when S became the limiting factor non protein nitrogen was increased.

Phosphorus content in grain and straw showed a decrease with sulphur application. Though nonsignificant, at lower levels of sulphur, at higher levels it drastically declined. This decline in phosphorus content did not reflect as such in removal, as the removal of P was influenced by yield increase due to higher levels of sulphur. The increase in P uptake is therefore seen to be high only upto S_{20} and the higher levels of sulphur application significantly reduced the P uptake and it was more or less similar to that in control plots. To put this in another way it can be inferred that at a given sufficient level of phosphorus the uptake is favourably influenced only at lower levels of sulphur and that too by the beneficial effect of sulphur in increasing yield. It is evident that there was antagonism in the content and removal of phosphorus with sulphur levels when the soil is rich in P, and P is fertilized at high levels. The reports available on sulphur x phosphorus interaction are rather conflicting. Large number of studies showed antagonistic relationship between these two elements and the possible explanation is that both sulphur and phosphorus are absorbed in anionic forms and may therefore compete with each other at the root absorbing site (Hasra, 1988). Tiwari (1990) found a significant negative interaction between P and S. Sulphur application increased S content but decreased P content in grain as well as in straw. Muraleedharan and Jose (1994) recorded similar antagonism of P in rice variety *Jyothi* with application of sulphur. In field experiments Aulakh *et al.* (1990) observed that at low levels of P and S, there was a synergetic effect of both. But with a high level such as 52.5 kg P ha^{-1} antagonistic effect of P x S on crop growth was noticed. In an earlier study Aulakh and Pasricha (1977) observed antagonism between P and S at all rates of their application. They inferred from their experiments that phosphorus fertilization of crops can be successfully undertaken in soils where there is enough available S. However, where sulphur is present in critical amounts, care must be taken in using large dressings of fertilizer phosphate because this will further aggravate sulphur deficiency by increasing the release of SO_4 in soil solution, already subjected to leaching losses in such soils. In this connection, it would be meaningful to discuss the differential relationship exhibited by phosphorus in Part II and Part III of the studies. In Part II, P had significant positive relationship with other nutrients including sulphur. But in Part III, phosphorus content decreased with increase in S levels. The reason for this differential response noticed in two occasions can be attributed to the absence or presence of high amount of sulphur in the two situations. Because, the relationship studied in Part II was in S_0 (control pots) and in Part III it was with sulphur application.

Potassium content of grain and straw, and uptake of potassium showed significant increase in APS as well as by higher levels. The increase was progressing even at the highest level of sulphur. It shows that there was synergetic influence for potassium with sulphur in absorbtion and uptake. Application of sulphur was found to increase the concentration of K in rice (Dev and Kumar, 1982; Singh, 1986 and Singh *et al.*, 1990). Aulakh and Pasricha (1977) observed a significant positive interaction between S and K in rape seed. Similar synergetic effect of K for application of S was reported by Muraleedharan and Jose (1994).

There was a decrease in calcium content in grain and straw in response to higher levels of calcium. The removal of calcium, however, increased in lower levels of sulphur but declined significantly with higher levels of sulphur. This shows that higher levels of sulphur had an antagonistic effect on content of calcium. The low content can be due to reduction in the calcium availability by precipitation as calcium sulphate. Calcium plays a role in the sorption of sulphate apart from fixation by calcium sulphate precipitation (Hesse, 1958). Kher and Singh (1993) reported that there was significant negative correlation between forms of sulphur and $CaCO_3$ content of soil.

Magnesium content in grain and straw increased with sulphur levels, but higher levels of sulphur decreased its content. This showed that there was a synergetic effect for magnesium to sulphur at lower levels which did not continue at higher levels or might have turned against. Eventhough, removal of magnesium by rice increased at lower levels since it declined at higher levels, it showed the importance of a balanced application of sulphur in getting good response from magnesium. No significant interaction was observed between S x Mg for crops like berseem and alfalfa. However, antagonistic interaction between S and Mg was observed in mustard (Hazra, 1988). Aulakh and Pasricha (1977) observed that application of sulphur decreased the uptake of magnesium. They further reported that the antagonism of Mg was not only with S but with K also. The synergetic effect of S x K on protein content and N:S ratio were also reported by Aulakh and Pasricha (1983).

The three micronutrients studied for their effect in response to sulphur application showed considerable variation between their levels as well as in relation to location and season. There was difference in the content of these nutrients in the two locations of experimentation. Zinc at lower levels generally increased the content but decreased at higher levels of sulphur. Both manganese and copper contents declined with low levels of sulphur. The uptake of zinc and manganese increased upto S_{20} but in the case of copper the uptake was high only upto S_{10} which showed that there was antagonism for these three elements with sulphur; and it was in higher magnitude in the case of copper. Karamanos (1989) reported that sulphur levels decreased the plant content and crop removal of copper in Canola. However they found that manganese induced copper deficiency was self corrected by application of sulphur. Tiwari (1991) observed an antagonistic relation between S and Zn wherein an increasing supply of S to soil caused significant decrease in Zn content of the plant. Mukhi and Shukla (1991) observed that zinc concentration and uptake in rice decreased with increasing S levels. Singh (1986) reported that at low levels of sulphur the relation between sulphur and zinc was synergetic but with higher levels of sulphur the relation seemed to be antagonistic due to interactions at absorbing sites.

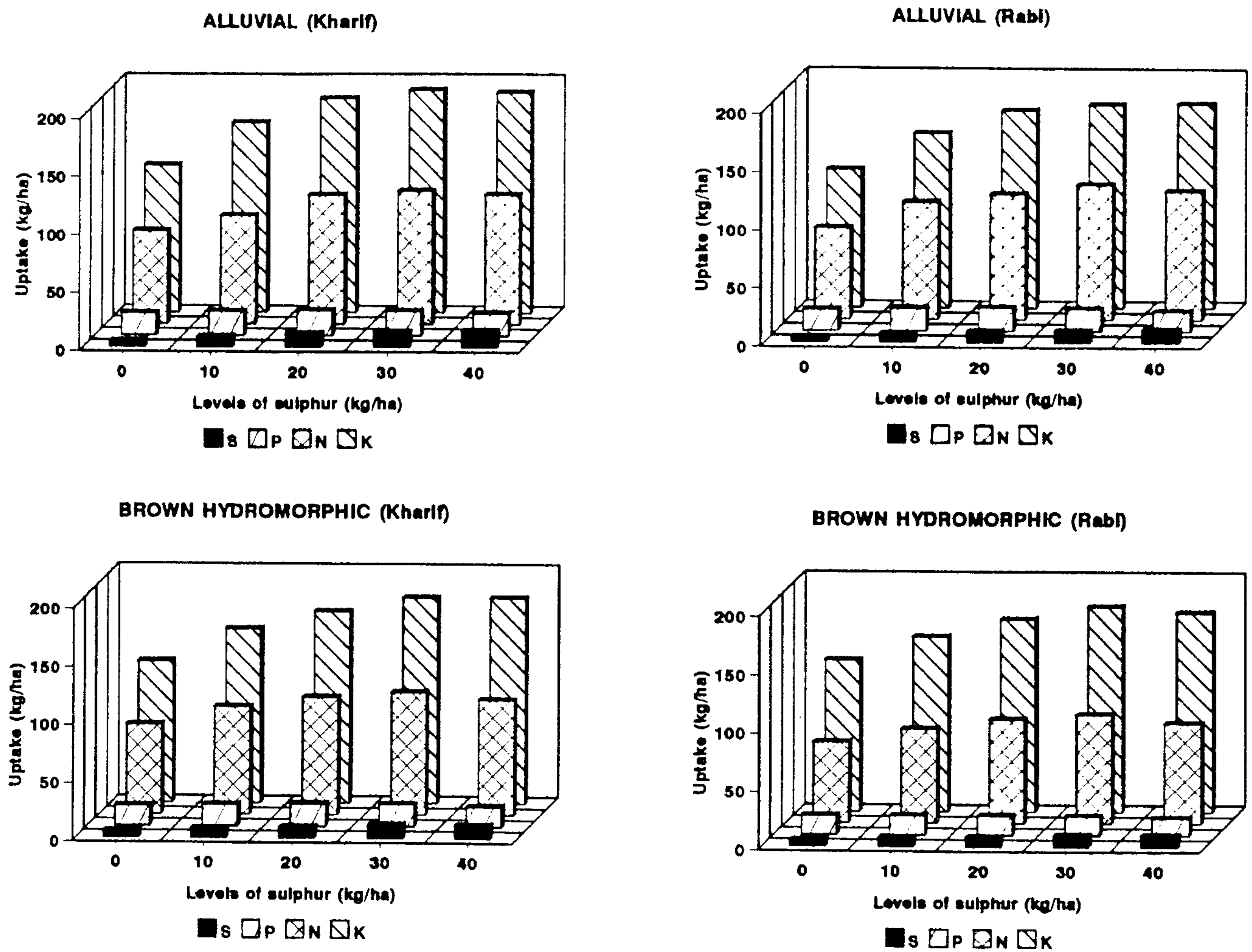


Fig. 34. **Relationship between uptake of Nitrogen, Phosphorus, Potassium and Sulphur**

Correlation between plant growth and yield parameters and plant nutrient uptake by rice in the four field experiments showed that growth and yield attributory parameters significantly and positively correlated with crop yield and nutrient uptake except with P. Similarly yield of crop (grain and straw) correlated with the uptake of sulphur, nitrogen and potassium. The quality of produce (protein content of grain and straw) was also significantly and positively correlated to other parameters. This shows that sulphur levels had positive significant influence on these parameters which showed the same trend of increases. The agronomic efficiency showed increase in APS than AS, and decrease from S_{10} to S_{40}. Agronomic efficiency being a measure of increase in yield with respect to control plot yield, under every level of nutrient applied, its high value means that the plant could use the applied sulphur more efficiently to produce grain yield. Therefore these results project that the source APS could more efficiently produce grain yield under sulphur nutrition than AS. The high value around 30 obtained in all the field experiments showed that S_{10} could very efficiently increase the yield over control. The decline in agronomic efficiency indicated that further additions of sulphur above 10 kg per hectare were not so efficient when compared with the lower levels in increasing yield. Physiological efficiency was highest when sulphur was applied @ 20 kg S ha^{-1}. Physiological efficiency being a measure of addition of drymatter production per addition of nutrient uptake, indicates that the drymatter increased significantly by S uptake upto 20 kg S ha^{-1} and the uptake of sulphur was also efficiently converted to drymatter upto the level of S_{20}. However, at the higher levels, the efficiency of conversion to drymatter yield by sulphur uptake declined. This again indicated that the lower levels were essentially eliminating S deficiency thereby crop yield was obtained whereas the higher levels build up S level in soil, as the recovery from deficiency is achieved by lower levels. The apparent recovery efficiency also showed the same trend. Being a measure of hike in nutrient uptake over that of control for every addition of S the result indicated that the recovery was more at lower levels of S. The findings in this study is in agreement with reports of Ismunadji *et al.* (1983) who observed that application of sulphur levels @ 15, 30 and 60 kg S ha^{-1} though increased the S recovery in grain by the rates of 4.23, 4.68 and 5.61 kg S ha^{-1}, decreased the apparent S recovery per cent as 7.1, 5.0 and 4.1 respectively. Per cent yield and per cent yield increase showed an upward trend in yield up to S_{40} and the highest yield increase was achieved upto S_{30}. Here again, the response ratio declined with increase in sulphur levels showing more efficiency for applied S at lower levels of S.

Gross income, net income and benefit : cost ratio showed that APS was superior to AS. The total income, net profit and B : C ratio have increased with sulphur application upto 30 kg S ha^{-1}. The results revealed that though there was increase in yield due to sulphur levels a negative trend was gradually noticed around the level of 30 kg S ha^{-1}. This is further elucidated by working out physical and economic optimum levels of these two sources by fitting quadratic response equation. The grain yield, straw yield and net return are high for alluvial soils compared to brown hydromorphic soils. The reason for this may be the higher fertility status of alluvial soil. The *Kharif* yield was higher in both locations. The higher yield in *Kharif* can be due to the advantage mainly of the preceding fallow period, and low weed presence. The regression equations and significant R^2 values indicated high degree of reliability on response function. The economic optimum levels showed that sulphur levels between 23 to 29 kg were economical for both the sources at both locations at both the seasons. A level above 29 kg was uneconomic. Tandon (1995)

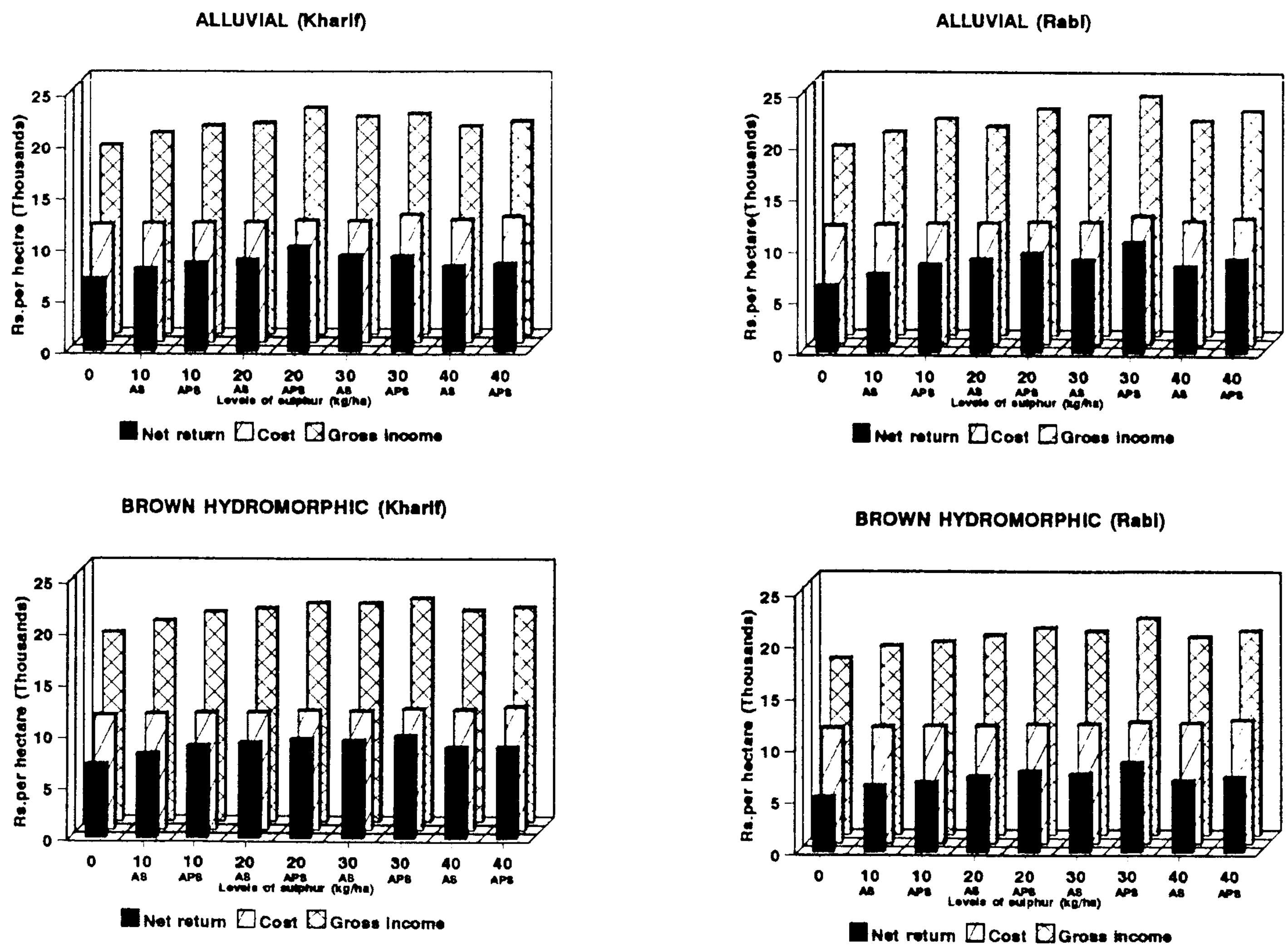


Fig. 35. **Economics of sulphur application**

suggested that the price of 1 kg S might be considered as Rs.3.65 for cost calculations to match the raw material cost since sulphur in still not formally priced. In the present study cost of cultivation has been considerably higher since (1) the value of fertilizer was estimated in relation to cost of substitute fertilizers of N and P such as urea and mussoriephos (2) the wage rate of labour in rice farming area is high (around Rs.70/- per day). These factors have pulled down the values of net return and benefit : cost ratio in general. This is evident in the observation that, while the highest benefit : cost ratio recorded in this study is only 1.853 the same was as high as 11.2 in the studies of Clarson and Ramaswamy (1992) in TNAU. The value:cost ratio was 13.6 in FAO sulphur trials (Tandon, 1995).

The results further showed that in general there was no residual effect for sulphur application upto 40 kg S ha^{-1}. However, in brown hydromorphic soils application of sulphur as AS @ 40 kg S ha^{-1} and as APS @ 30 and 40 kg S ha^{-1} leaves residual sulphur levels beneficial to the succeeding crop. In other words the higher level of S @ 40 kg helped to increase yield in the succeding crop even though it did not improve yield in *Kharif* compared to lower level of 30 kg S ha^{-1}. However, this effect was not seen in straw yield. The lack of residual effect of S as was seen generally, might be due to leaching. Sulphate is readily leached from light textured soils. Sulphate leached from top soil is retained further down the profile by a clay layer (Neller, 1959). If there is an underlying impervious layer leaching may also occur in a lateral rather than a vertical direction (Barrow *et al.*, 1969). Studies showed that, eventhough considerable amount of S was added to the soil through single super phosphate, it was not reflected to the same extent in the build up of available sulphur suggesting considerable loss through leaching (Tiwari, 1990). It was also reported that there was a negative balance of S where diammonium phosphate was applied. Karamanos and Janzen (1991) reported that the absence of residual benefits of sulphur application could be due to climatic conditions.

5.4 Part-IV. Sulphur use efficiency of rice (SUE)

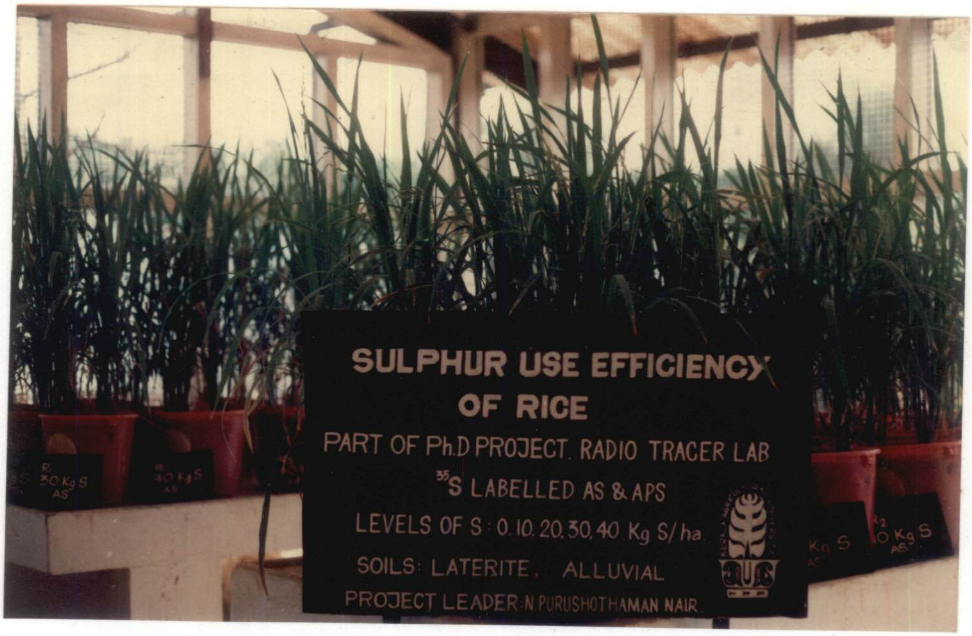
An experiment was conducted at Radio Tracer Laboratory, Kerala Agricultural University, Vellanikkara during 1992-93 to evaluate the sulphur use efficiency of rice in two types of soils viz. alluvial and brown hydromorphic. Two sources of ^{35}S tagged S fertilizers viz. ammonium sulphate and ammonium phosphate sulphate were evaluated with levels of S @ 10, 20, 30 and 40 kg S ha^{-1} with a control (S_0 - no sulphur). The results of the experiment are discussed here under:

Specific activities (dpm μg^{-1} S) in grain, straw and whole plant in both soil types - alluvial and brown hydromorphic - and their pooled analysis showed that the specific activities in grain and whole plant were high for the source ammonium phosphate sulphate. The specific activities due to sulphur levels showed that it increased in both locations progressively with increase in S levels. Highest values of specific activity obtained were in pots applied with 40 kg S ha^{-1} as APS. From the pooled data it could be seen that the specific activity was high in straw when S was supplied as AS. On the other hand S application through APS resulted in higher specific activity in grain. This may be the reason for APS to show a higher significant specific activity in grain, which was absent in straw.

In alluvial soils the yield of grain, straw and biomass increased with sulphur application upto 20 kg S ha^{-1}. There after the increase was not significant with higher levels. However, the total sulphur content increased upto 30 kg S ha^{-1}.

Plate 9. A view of pot culture to study the sulphur use efficiency with ^{35}S labelled AS and APS, in brown hydromorphic soil of RARS, Pattambi

Plate 10. Rice grown in alluvial soil of CSRC, Karamana, showing poor performance under control compared to S applied (as ^{35}S labelled AS).



SULPHUR USE EFFICIENCY
OF RICE
PART OF Ph.D PROJECT. RADIO TRACER LAB
35S LABELLED AS & APS
LEVELS OF S: 0, 10, 20, 30, 40 Kg S/ha.
SOILS: LATERITE, ALLUVIAL
PROJECT LEADER: N PURUSHOTHAMAN NAIR

R1 40 Kg S
R1 30 Kg S
R1 20 Kg S
R1 10 Kg S
R1 0 Kg S

In brown hydromorphic soils the yield as well as the S uptake increased in APS applied pots than in AS applied pots. Here the higher sulphur levels helped to increase the yield and uptake of sulphur progressively. Similar results have been reported by Sachdev *et al.* (1982) and Sreemannarayana and Sreenivasaraju (1994). Pooled analysis of data of both soils showed that in controlled conditions (pot culture) brown hydromorphic soils showed higher yield and higher uptake of sulphur compared to alluvial. The higher uptake of S in grain and yield (as seen from pooled data) due to APS can be explained as a result of higher specific activity by APS. The increase in yields of grain and straw and the total sulphur uptake showed that the higher levels progressively and beneficially acted and are justified by the higher specific activities seen with higher sulphur levels. Yield and nutrient uptake were higher in brown hydromorphic soils. This is contradictory to the results obtained in field experiments where the mean yields were high in alluvial soils. The lower yields obtained in brown hydromorphic location (Pattambi) compared with that of alluvial soil location (Karamana) can be due to climatic differences and soil fertility variations between the places. Further interaction of environmental and seasonal conditions cause considerable fluctuations in levels of soluble sulphate in surface soil (Tisdale *et al.*, 1985).

Utilization of native and applied sulphur in alluvial soil showed that Sdff increased significantly upto 30 kg S ha^{-1}. Similar results were reported by Sharma and Kamath (1991) and Subramanian *et al.* (1991). On the other hand Sdfs significantly decreased upto 30 kg S ha^{-1}. The sulphur use efficiency was highest at 20 kg S ha^{-1}. SUE declined at highest level of 40 kg S ha^{-1}. These results indicate that the higher levels of sulphur application above 20 kg S ha^{-1} gave higher contributions to plants in uptake but not in yield. This is evident from the quantity of sulphur in plant

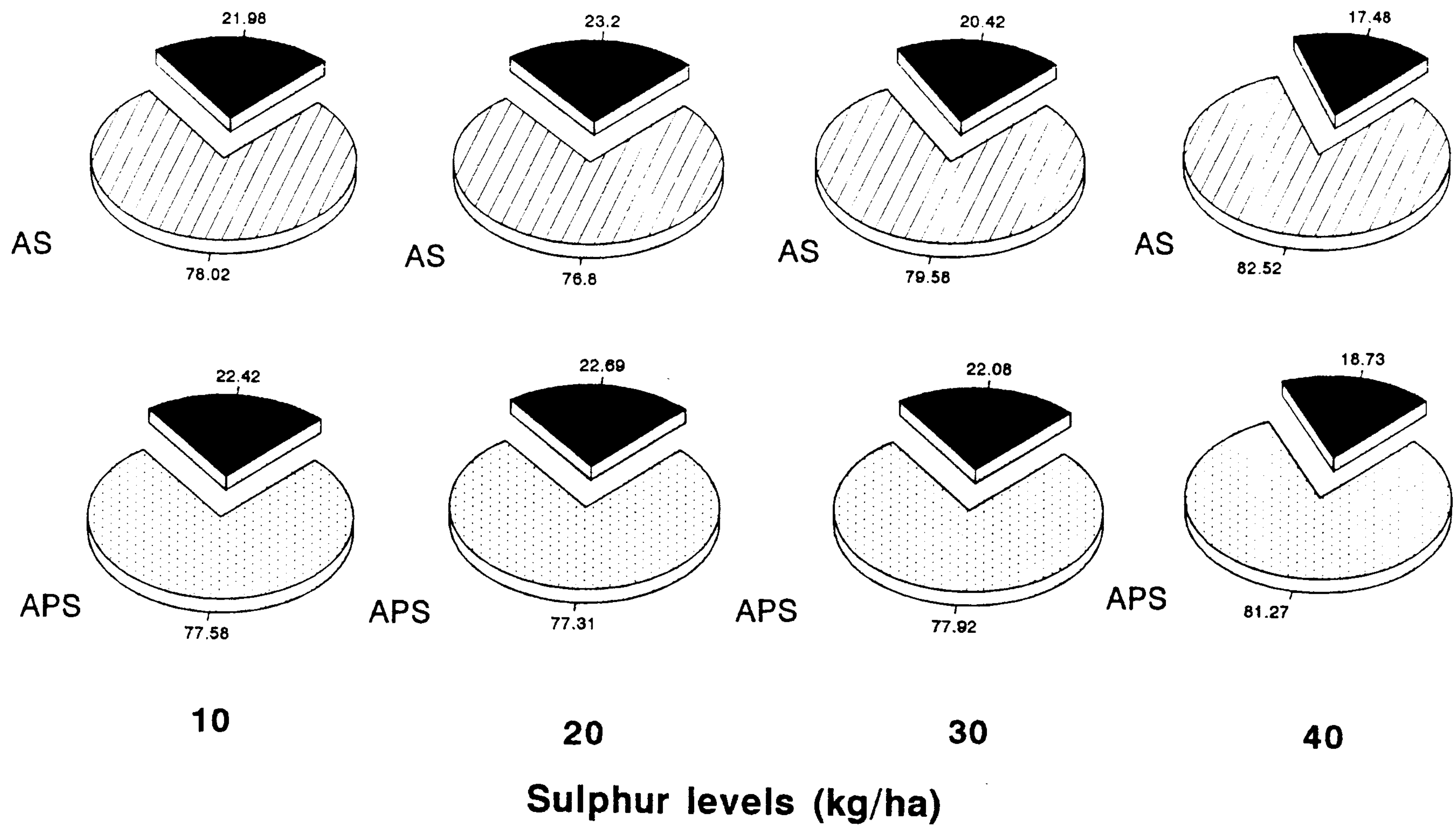


Fig. 36. **Sulphur use efficiency in alluvial soil under different levels of sulphur**

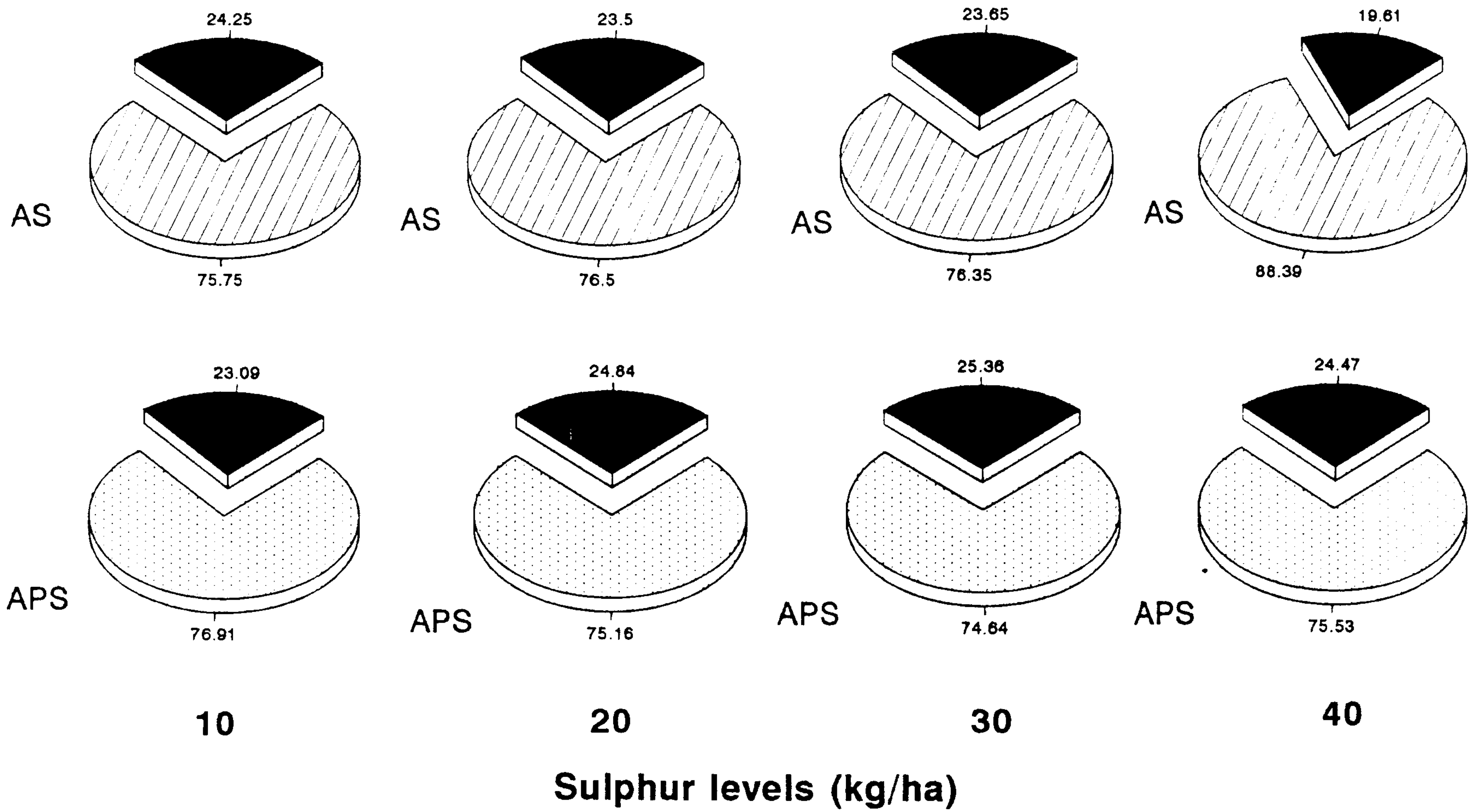


Fig. 37. **Sulphur use efficiency in Brown hydromorphic soil under different levels of sulphur**

taken up from fertilizer, which progressively and significantly increased upto 40 kg S ha^{-1}. The A-values were on par. This indicated that soil contributions to the rice plant in S deficient alluvial soil was not appreciable and the sulphur removed by the rice plant depended on and in proportion to the fertilizer applied. In brown hydromorphic soils Sdff increased progressively with higher levels. Similar results were reported by Venkateswarlu (1971) and Marok and Dev (1980). On the contrary Sdfs declined with higher levels of S. Sulphur in plants taken up from fertilizer increased with higher levels of S. A-value and SUE were on par. The results indicated that the sulphur requirement of plants were met from applied fertilizer in direct proportion and soil contribution was negligible. Similar results were reported by Dhillon and Dev (1978). The SUE in brown hydromorphic soil was highest at 30 kg S ha^{-1} but statistically all the levels showed same level of efficiency. The pooled analysis for both soils showed that SUE was highest at 20 kg S ha^{-1}. Sulphur derived from fertilizer was higher for alluvial soil. But sulphur in plant taken up from fertilizer was high for brown hydromorphic soil. SUE and A-value were higher for brown hydromorphic soil. The higher A-value in brown hydromorphic soil is justified by the higher Sdfs in that soil. Even though %Sdff is more in alluvial soils, the higher quantity of S taken from fertilizer, and the trend of higher SUE in brown hydromorphic soils might be the reasons for higher yield and higher uptake of sulphur by this soil. The increase in the sulphur use efficiency by APS can be justified in the light of the findings of Clarson and Ramaswamy (1992) who noticed that SUE was high for APS (21.1%) compared to AS (12.5%).

5.5 Future line of work

In the light of this study it is suggested that similar detailed studies on response of sulphur on the major crop components of other cropping systems of the state can be taken up which will be of great practical significance in achieving higher agricultural production. As such comprehensive and detailed assessment of status and availability of sulphur in soils where coconut is grown and the response of coconut to sulphur fertilization are to be studied with priority which may be of great utility to the farmers of the state in improving coconut production since oil yielding crops have high demand for sulphur.

Summary

6. SUMMARY

A series of investigations were undertaken entitled "Status and availability of sulphur in the major paddy soils of Kerala and response of rice to sulphatic fertilizers" at College of Horticulture, Kerala Agricultural University, Vellanikkara, during 1990-1994 with the objectives (i) to assess the sulphur status of major paddy soils of Kerala (viz. alluvial and brown hydromorphic) (ii) to identify an appropriate chemical method of evaluating available sulphur in these soils (iii) to determine the critical levels of sulphur in these soils (iv) to study the response of two popular sulphatic fertilizers of Kerala (viz. ammonium sulphate and ammonium phosphate sulphate) and (v) to evaluate the sulphur use efficiency by ^{35}S tracer method. The whole study was divided in to four parts and the results are summarised here under.

6.1 Part-I. Assessment of the sulphur status of rice soils of Kerala

The sulphur status was estimated from 210 soils collected @ 105 samples each from alluvial and brown hydromorphic soils from 10 important rice growing districts of the state based on the area of rice in each districts. The parameters used to evaluate status were soluble SO_4-S, adsorbed SO_4-S, total sulphur and organic + non-SO_4-S. The delineation of soils in to low, medium and high (deficient, satisfactory and good) categories was done based on soluble SO_4-S as extracted by 0.15 per cent $CaCl_2$. It was observed that 56 per cent of soil samples in alluvial type were deficient in sulphur. Deficiency percentage was high in samples from Kollam district and low in Alappuzha (16%). About 36 per cent of the samples fell in highly deficient category (< 5 ppm). The range of soluble SO_4-S was 0.9 to 236.1 with the mean value of 16.89 ppm. The range of total sulphur was 63.6 to 2204.5 ppm with the mean value 302.89 ppm.

In brown hydromorphic of soil, 83 per cent of the area samples fell under deficiency level. More than 50 per cent of the soils were having less than 5 ppm sulphur. The mean soluble SO_4-S in brown hydromorphic soil was 7.02 (deficiency level) and the range was 0.9 to 67.8 ppm. Among the districts, soils of Malappuram had higher sulphur status.

The over all status of rice soils showed that 70 per cent of the rice soils are in deficient level. Out of 210 samples studied, 37 (18 % of the total) showed high level of sulphur. The soil sulphur status was found to correlate positively and significantly with organic carbon. Significant negative correlation was obtained between sulphur and pH of soil.

6.2 Part-II. Identification of suitable soil test procedure for estimation of available S

Based on delineation of soils in to low, medium and high in sulphur, thirty soils each from alluvial and brown hydromorphic, representing different categories of S status, were collected and the available SO_4-S content was estimated by 12 different methods of extractation. The methods tried were extraction with water, NaCl, NH_4OAc, $CaCl_2$, Bray's method (NH_4F + HCl), NH_4OAc + HOAc, $Ca(H_2SO_4)_2$, KH_2PO_4, $Ca(H_2PO_4)_2$ + HOAc, Morgan's extractant (NaOAc + HOAc), Olsen's reagent ($NaHCO_3$) and NH_4Cl. Correlations between different extractants and relative yield of grain, relative yield of straw, relative biomass production, grain yield, sulphur content in grain, straw yield and sulphur content in straw were studied for both soils. Estimation of critical levels were made for each extractant in both the soils by Cate and Nelson method. Critical levels in alluvial soil under the different methods were water - 7 ppm, NaCl - 8 ppm, NH_4OAc - 13 ppm, NH_4F + HCl - 13 ppm, $CaCl_2$ - 5 ppm, NH_4OAc + HOAc - 15 ppm, $Ca(H_2PO_4)_2$ - 15 ppm, $Ca(H_2PO_4)_2$ + HOAc - 15 ppm, KH_2PO_4 - 15 ppm, NaOAc + HOAc - 11 ppm, $NaHCO_3$ - 22 ppm and NH_4Cl - 7 ppm.

Based on the estimated critical levels the responsiveness of the different extractants were studied and found that in alluvial soil use of $Ca(H_2PO_4)_2$ was the best extraction method among the 12 methods tried. The next best was NH_4OAc + HOAc.

Critical levels in brown hydromorphic soils by the 12 extraction methods were studied and the levels were water - 6 ppm, NaCl - 10 ppm, NH_4OA - 15 ppm, $CaCl_2$ - 10 ppm, NH_4F + HCl - 10 ppm, NH_4OAc + HOAc - 13 ppm, $Ca(H_2PO_4)_2$ - 17 ppm, KH_2PO_4 - 16 ppm $Ca(H_2PO_4)_2$ + HOAc - 10 ppm, NaOAc + HOAc - 16 ppm, $NaHCO_3$ - 20 ppm and NH_4Cl - 8 ppm. The responsiveness of different soils to application of 40 kg S ha^{-1} was evaluated and based on that the best methods of extraction were identified. In brown hydromorphic soil, monocalcium phosphate + acetic acid, monocalcium phosphate, Morgan's extractant and Calcium chloride, in the order as shown above, were found more suitable for sulphur status estimation.

The correlation between soil SO_4-S and plant content of N, K and S showed significant correlation in both the soils. Soil SO_4-S was correlated positively and significantly with grain yield, relative biomass yield, grain sulphur content and straw sulphur content. The transformed values of score for presence of green algae significantly and negatively correlated with soil SO_4-S, relative biomass yield, straw S content and grain S content in both the soils.

The critical sulphur concentration in plant (straw) at harvest was estimated by Cate and Nelson method which showed that the critical concentration in alluvial soil was 0.075 per cent, and in brown hydromorphic soil 0.08 per cent.

6.3 Part-III. Response of rice to different levels and source of sulphur

Two locations, one each in alluvial and brown hydromorphic soil types, were identified for studying the response of rice to sulphatic fertilizers. Field experiments were laid out at these locations (CSRC, Karamana - alluvial and RARS, Pattambi - brown hydromorphic) which were deficient in soil SO_4-S, for two seasons, *Kharif* and *Rabi* of 1992-93, with 9 treatments (viz. control, ammonium sulphate (AS) @ 10, 20, 30 and 40 kg S ha^{-1} and ammonium phosphate sulphate (APS) @ 10, 20, 30 and 40 kg S ha^{-1}) and 3 replications in 2 x 4 + 1 factorial RBD. The results of field experiments showed that:

Ammonium phosphate sulphate increased height of plants, leaf area index at 60 DAT at alluvial soil and number of tillers during *Kharif* season in both soils over those by ammonium sulphate. Sulphur levels increased height of plants, leaf area index and total tillers over control and lowest level.

Yield of grain significantly increased by APS over that by AS. Sulphur application progressively increased grain yield upto 30 kg S ha^{-1}. Yield of straw was significantly increased by sulphur application over control.

Number of productive tillers per m^2 increased by application of APS over that by AS. Sulphur application increased number of productive tiller upto 30 kg S ha^{-1}. Number of grains per earhead, percentage of mature grains, weight of panicle, test weight of grain (1000 grain weight) and dry matter production at maturity, increased with higher levels of sulphur application. Grain : Straw ratio and harvest index were on par. Sink capacity increased with APS and higher levels of sulphur. The infestation of gall fly increased with sulphur application. Green algae presence decreased with sulphur levels.

Content of sulphur in grain and straw increased in APS applied plots. Higher levels of sulphur progressively increased sulphur content of grain and straw. Sulphur uptake increased by APS and higher levels of sulphur.

Nitrogen content in grain and straw increased with sulphur application over control. Uptake of nitrogen increased by APS as well as higher levels of sulphur upto 30 kg S ha^{-1}.

Phosphorus content in grain and straw decreased with sulphur application. But uptake of P was on par, except at *Kharif* season in alluvial where the lower levels of sulphur increased P uptake.

Potassium content of grain and straw increased by APS and application of S upto 40 kg S ha^{-1}. Potassium uptake increased by APS and higher levels of sulphur upto 30 kg S ha^{-1}.

Calcium content of grain and straw increased by higher levels of sulphur. Application 10 and 20 kg S ha^{-1} increased calcium uptake over other levels.

Magnesium levels increased magnesium content of grain and straw at lower levels; however the higher levels decreased magnesium content. Magnesium uptake also showed the trend of the content.

Zinc content increased at lower levels but decreased significantly at 40 kg S ha^{-1}. Zinc uptake also increased at low levels of sulphur; however it decreased at the highest level of S.

Manganese content of grain and straw as well as manganese uptake decreased at higher levels of sulphur. Similarly, copper content of grain and straw and the uptake of copper declined at the highest level of sulphur.

Sulphur application increased the sulphur uptake; and the removal per ton of grain was increased from 0.65 to 0.95 kg, and in straw the removal per ton of straw increased from 0.58 to 1.33 kg.

The N : S ratio in grain changed by sulphur application from 17 to 13 and in straw from 13.2 to 6.6. The P : S ratio also improved from 4.0 to 2.5 in grain and 2.6 to 1.5 in straw. The K : S ratio declined from 5.5 to 4.4 in grain and from 37.1 to 28.5 in straw. Favourable reduction in the Ca : S and Mg : S ratio were seen by sulphur application.

Protein content improved by APS over that in AS. The sulphur application improved the protein content in grain and straw.

Significant positive correlations were found in all the four field experiments between yield attributes, yield of grain and straw, quality of grain, straw (protein) and uptake of macro nutrients.

Agronomic efficiency, physiological efficiency and apparent recovery efficiency were high for lower levels of sulphur and declined with increase in sulphur dose.

While response ratio declined, per cent yield and per cent increase in yield increased with higher level of sulphur application upto 30 kg S ha^{-1}.

Gross income, net income and B : C ratio increased in APS compared to AS. Sulphur application increased these values and the highest values were obtained to 30 kg S ha^{-1}.

Grain yield, straw yield, net return and B : C ratio were higher in alluvial soil compared to brown hydromorphic soil. Yield of grain, net return and B : C ratio were higher in *Kharif* season than in *Rabi* season.

The economic optimum levels of AS and APS were 26.75 (27) and 24.90 (25) kg S ha^{-1} respectively. The mean physical optimum and economic optimum levels were 28.55 and 25.81 kg S ha^{-1}. There was no residual effect of sulphur application below 30 kg S ha^{-1} to the grain yield of succeeding crop in brown hydromorphic soil. In alluvial soil there was no residual effect for sulphur levels..

6.4 Part IV. Sulphur use efficiency of rice

The specific activity in grain and straw increased with increase in sulphur application in both soils. Higher levels of sulphur applied as ^{35}S increased the uptake of S by straw and grain in both the soils. Parameters like, grain yield, straw yield, total dry matter yield and removal of S by plant parts increased by higher doses of

^{35}S in both soils. Yield and uptake of nutrients were more in brown hydromorphic soils compared to alluvial soil in green house conditions.

Sdff increased with increase in S levels. Sulphur use efficiency was highest at 20 kg S ha^{-1} and declained at 40 kg S ha^{-1} in alluvial soil. In brown hydromorphic soil SUE was highest at 30 kg S ha^{-1} with decrease at 40 kg S ha^{-1}. A values were on par under sulphur levels.

Sdff was high for alluvial soil. But Sdfs, utilization of applied sulphur and sulphur taken up from fertilizer were high for brown hydromorphic soil.

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* Originals not seen

Appendices

APPENDIX-I

Area (in ha) under rice* in 10 major rice growing districts of Kerala (1989)

District	Total (ha)	Alluvial soil (ha)	Brown hydromorphic soil (ha)
Palakkad	154864	83180	71684
Thrissur	89527	56976	32551
Ernakulam	80817	14050	66767
Alappuzha	67835	51532	12333
Malappuram	62308	44900	17408
Kottayam	33603	9190	24413
Kollam	32824	4355	28469
Thiruvananthapuram	25444	11575	13869
Kannur	26961	9924	17037
Kozhikode	18123	700	17423

*Source: Kerala State Land Use Board, Thiruvananthapuram

APPENDIX-I(a)

Locations/Padasekharams from where samples were collected for assessing sulphur status (Alluvial soil)

Sample No.	Location	District
1	Chalissery	Palakkad
2	Alathur	,,
3	Erumayur	,,
4	Olavakkodeu	,,
5	Palappata	,,
6	Puthupariaram	,,
7	Kulankanda	,,
8	Muttukkulangara	,,
9	Valayakkad	,,
10	Mullakkarapadam	,,
11	Pottakkulam	,,
12	Kavalpatta	,,
13	Coyalmannam	,,
14	Kannampra	,,
15	Poomodupadam	,,
16	Pandarakkad	,,
17	Thottampadam	,,
18	Ammoorpadam	,,
19	Vadanakurichipadam	,,
20	Pattarukandam	,,
21	Thiruvonapurampalliyal	,,
22	Anangattupadam	,,
23	Manjalungalpaddam	,,
24	Chalappuram	,,
25	Perumpadapala	,,
26	Kundipadam	,,
27	Vavanur	,,
28	Kodalilpadam	,,
29	Parayilpadam	,,
30	Chalakkudy ARS	Thrissur
31	Purakkattil	,,
32	Chuvannamannu	,,
33	Kannara	,,
34	Vazhukkamparam	,,
35	Pallikandam	,,
36	Puthupparakandam	,,
37	Mupathupadam	,,
38	Valiakannankoddu	,,
39	Pattayilpadam	,,
40	Manjangappadam	,,
41	Thanippadam	,,

Contd.

Appendix-I(a). continued

1	2	3
42	Nadathara	,,
43	Eravimangalam	,,
44	Puthoorpadam	,,
45	Kaladipadinjarepadam	,,
46	Palloopadam	,,
47	Pattikkadu	,,
48	Thavanur SSF	Malappuram
49	Mundakapadam	,,
50	Moovankarapadam	,,
51	Karuthalpadam	,,
52	Karakkurinilam	,,
53	Maravancherry Kayal	,,
54	Mangattupadam	,,
55	Padikkaparambu	,,
56	Polpakkara	,,
57	Unikattepadi	,,
58	Edappanpadam	,,
59	Kariparambu	,,
60	Viyyam	,,
61	Chellipadam	,,
62	Pullaninilam	,,
63	Kundothipadam	,,
64	Thavanur KCAET Block S	,,
65	Thavanur KCAET Blcok F	,,
66	Varaniparambu Punja	Ernakulam
67	Kidangoorpadam	,,
68	Kaipathur	,,
69	Kalady	,,
70	Moncompu RRS	Alappuzha
71	Pulinkunnu	,,
72	Nedumudy	,,
73	Kayamkulam ARS	,,
74	Valiakulangara	,,
75	Mannar	,,
76	Pu[illegible]kkadu	,,
77	Maveliparambu	,,
78	Pullikanakku	,,
79	Mampuzhakkari	,,
80	Ramankari	,,
81	Champakkulam	,,
82	Ponga	,,
83	Edathua	,,
84	Veeyapuram	,,

Contd.

Appendix-I(a). Continued

1	2	3
85	Kurattissery	,,
86	Anaparambal	,,
87	Vavvakkavu	Kollam
88	Thazhava	,,
89	Chempooru	Thiruvananthapuram
90	Aruvikkara	,,
91	Athiyannur	,,
92	Parasuvakkal	,,
93	Karamana CSRC	,,
94	Attoorpadam	Thrissur
95	Kidangara	Kottayam
96	Kurichi	,,
97	Vazhapalli	,,
98	Oorpalli	Kannur
99	Champad	,,
100	Munderi	,,
101	Thazhachowa	,,
102	Changamkulam	Thrissur
105	Thiruvanchikkulam	,,
104	Mathoorpadam	Alappuzha
105	Vezkapra	,,

APPENDIX-I(b)

Locations/Padasekharams from where samples were collected for assessing sulphur status (Brown hydromorphic soil)

Sample No.	Location	District
1	Dhoni	Palakkad
2	Nechupully	,,
3	Poomodupadam	,,
4	Pandarakkad (Manpottakulam)	,,
5	Kannancode	,,
6	Vadakkenchery	,,
7	Puthoorkkulam	,,
9	Panniankara	,,
10	Pattambi A-Block RARS	,,
11	Pattambi B-Block	,,
12	Pattambi H-Block	,,
13	Pattambi Modan	,,
14	Vadanakurichi	,,
15	Koppam	,,
16	Vavanur	,,
17	Sankaramangalam	,,
18	Kattilmedupadam	,,
19	Nariamthodu	,,
20	Thekkumuri	,,
21	Kallooparampu	,,
22	Choorkunnupadam	,,
23	Nadathippara	,,
24	Parakkandam	,,
25	Kuzhikkandam	,,
26	Kainikattu	Thrissur
27	Kulangarapadam	,,
28	Pottakkandam	,,
29	Mannuthy IF B-2	,,
30	Mannuthy IF B-3	,,
31	Mannuthy SSF	,,
32	Koratty	,,
33	Ollookkara	,,
34	Kainikkattu Thekkoottupadam	,,
35	Erinjikulampadam	,,
36	Perumipilavu	,,
37	Karukutty	Ernakulam
38	Karayamparambu	,,
39	Mookkannur	,,
40	Nakkilipadam	,,
41	Koorampil	,,

Contd.

Appendix-I(b). Continued

1	2	3
42	Mundapally	,,
43	Mathoorpadam	,,
44	Kaipathoor	,,
45	Thirumarady	,,
46	Pampakkuda	,,
47	Anchelpetti	,,
48	Ankamalipalampadam	,,
49	Okkalpadam	,,
50	Manthodipadam	,,
51	Mannurpadam	,,
52	Marangattupadam	,,
53	Plankudipadam	,,
54	Kavupallithuruthu	,,
55	Karasickaparambu	,,
56	Puliyoor	Alappuzha
57	Cherianad	,,
58	Kunnathuthazhayilpadam	,,
59	Alacode	,,
60	Puthoor	,,
61	Pampanam punja	,,
62	Thuiyyam	Malappuram
63	Kariparambu	,,
64	Vempalli	Kottayam
65	Puthuvelil	,,
66	Kottamkompu	,,
67	Urukuzhi	,,
68	Kozha East	,,
70	Kozha West	,,
70	Kuravilangadu	,,
71	Pakalomattam	,,
72	Kunnankodu	Kollam
73	Murukkumon Ela South	,,
74	Murukkumon Ela North	,,
75	Chadayamangalam	,,
76	Plakkottupadam	,,
77	Valakom	,,
78	Vayakkal	,,
79	Ayoor	,,
80	Nilamel	,,
81	Mullapallipadam	,,
82	Chakkiara Ela	,,
83	Marangattukonam	,,
84	Mannanthala	Thiruvananthapuram

Cont.

Appendix-I(b). Continued

1	2	3
85	Irumba	,,
86	Valiavila	,,
87	Ottasekharamangalam	,,
88	Maruthur Ela	,,
89	Karakulam	,,
90	Kizhayikonam	Kollam
91	Chelampra	Kozhikkodu
92	Kundayithode	,,
93	Meppayur	,,
94	Panur	Kannur
95	Ayyappanthodu	,,
96	Kaithachal	,,
97	Vengad	,,
98	Arakkinar	,,
99	Thilannur	,,
100	Karyattupuram	,,
101	Kandanakom	Malappuram
102	Paikannur	,,
103	Valancherry	,,
104	Vattappara	,,
105	Edarikkadu	,,

APPENDIX-II(a)

Analytical data of sulphur status and properties of alluvial soil

Sample No.	Soluble SO_4-S (ppm)	Adsorbed SO_4-S (ppm)	Total S (ppm)	pH	Organic carbon (%)
1	8.2	4.1	132.0	5.6	0.75
2	4.1	2.3	90.9	5.2	0.60
3	15.5	3.6	172.7	4.8	0.83
4	10.9	5.9	165.3	4.9	0.87
5	17.3	5.0	178.4	4.7	0.87
6	14.1	5.5	168.5	5.1	0.79
7	9.1	3.2	122.9	5.4	0.64
8	4.6	11.8	212.1	5.8	0.79
9	4.6	5.4	122.7	6.1	0.53
10	10.0	5.5	190.9	5.7	0.72
11	2.7	3.7	113.6	6.3	0.56
12	10.5	1.8	186.3	5.7	0.68
13	8.2	5.9	213.6	5.5	0.76
14	14.1	9.7	318.9	5.9	0.83
15	9.6	3.1	212.1	6.7	0.76
16	18.20	10.5	349.9	6.2	0.95
17	4.6	2.7	218.2	5.3	0.79
18	11.4	7.4	218.2	5.7	0.72
19	4.6	1.8	113.6	5.6	0.60
20	0.9	5.9	109.1	5.1	0.60
21	2.3	7.7	204.5	6.5	0.76
22	3.2	4.1	140.9	6.2	0.60
23	4.1	4.5	159.1	5.9	0.72
24	2.3	5.0	204.5	5.7	0.68
25	2.3	5.0	190.9	6.2	0.60
26	4.6	5.0	218.2	4.9	0.79
27	4.6	5.0	199.9	4.8	0.72
28	4.6	3.6	177.3	4.9	0.64
29	11.8	19.6	272.7	5.7	0.98
30	6.4	1.8	72.7	6.6	0.41
31	6.4	2.7	127.3	4.8	0.41
32	10.0	5.5	127.3	4.8	0.53
33	15.5	2.7	181.8	4.7	0.56
34	8.2	8.2	192.7	5.8	0.60
35	2.3	4.5	113.6	5.9	0.56
36	4.6	4.5	99.9	6.2	0.49
37	9.1	11.4	168.2	4.9	0.45
38	9.1	13.7	218.2	4.7	0.56
39	2.3	6.8	86.3	6.8	0.64

Contd.

Appendix-II(a). Continued

1	2	3	4	5	6
40	9.6	10.0	209.0	4.9	0.41
41	9.1	20.5	240.9	4.9	0.68
42	10.9	8.7	204.5	6.0	0.72
43	4.6	9.5	222.7	4.8	0.68
44	4.6	19.5	222.7	4.9	0.72
45	2.3	6.8	127.3	5.9	0.72
46	2.3	16.4	218.2	5.2	0.49
47	6.4	10.5	177.3	6.2	0.60
48	9.1	13.2	218.2	6.1	0.64
49	4.6	3.6	172.7	4.8	0.53
50	3.6	6.8	213.6	4.9	0.64
51	20.0	9.6	240.9	5.2	0.64
52	2.3	6.3	199.9	4.8	0.83
53	22.3	10.0	445.4	4.3	2.23
54	18.7	1.8	218.2	5.2	0.83
55	13.2	32.3	418.2	4.3	1.89
56	30.5	11.8	436.4	4.2	2.19
57	4.6	4.0	99.9	6.5	0.49
58	30.0	29.2	672.7	4.3	2.53
59	28.7	10.9	41,36	4.4	2.15
60	4.6	10.9	236.4	5.1	0.98
61	86.5	149.6	690.9	4.6	1.92
62	6.4	20.4	268.2	4.7	1.10
63	4.6	4.0	109.1	6.4	0.60
64	15.6	5.8	249.7	5.9	0.72
65	4.6	22.7	231.6	5.8	0.72
66	9.6	16.8	213.6	5.4	0.68
67	4.6	1.8	118.2	6.2	0.53
68	13.2	5.0	163.6	6.4	0.76
69	4.6	5.0	159.1	6.7	0.64
70	23.2	61.9	1218.2	3.9	3.29
71	21.4	59.1	981.8	4.9	3.10
72	28.2	55.1	1027.3	4.5	3.33
73	10.5	5.0	63.6	6.5	0.41
74	6.4	1.8	72.7	6.7	0.37
75	2.3	5.9	118.2	6.4	0.49
76	236.1	510.1	1859.1	4.0	3.48
77	216.1	621.1	2204.5	3.9	3.63
78	13.2	6.4	218.2	4.6	0.72
79	22.8	56.4	754.5	4.6	2.96
80	24.1	58.3	809.1	4.4	3.00
81	26.4	57.3	872.7	5.1	3.03
82	24.6	55.0	786.4	4.9	3.03

Contd.

Appendix-II(a). Continued

1	2	3	4	5	6
83	24.1	39.6	872.7	4.7	2.72
84	139.2	209.3	1127.2	4.7	3.22
85	4.6	1.8	163.6	6.4	0.72
86	18.2	8.6	236.4	5.7	0.83
87	2.3	2.2	99.9	5.3	0.41
88	4.6	1.8	63.6	5.8	0.37
89	2.3	2.3	86.4	6.4	0.41
90	8.2	7.3	109.0	5.4	0.53
91	12.3	5.9	95.5	6.3	0.41
92	15.5	5.0	236.7	5.2	0.76
93	6.4	2.2	145.5	5.9	0.68
94	0.9	3.6	77.3	6.4	0.41
95	18.6	55.5	798.6	4.5	3.29
96	15.5	50.0	625.4	4.6	2.96
97	17.5	54.3	734.5	4.6	3.21
98	4.1	5.0	190.9	5.7	0.72
99	3.6	4.6	172.7	5.8	0.60
100	13.2	26.3	280.8	5.8	0.83
101	9.1	10.9	168.2	5.9	0.68
102	9.6	6.0	118.2	5.7	0.72
103	38.2	59.5	354.5	6.7	1.58
104	29.5	52.9	672.7	4.8	2.78
105	26.4	52.8	699.9	4.6	2.61

APPENDIX-II(b)

Analytical data of sulphur status and properties of brown hydromorphic soil

Sample No.	Soluble SO_4-S (ppm)	Adsorbed SO_4-S (ppm)	Total S (ppm)	pH	Organic carbon (%)
1	2.3	1.8	113.6	5.5	0.45
2	6.4	3.6	172.7	5.6	0.53
3	22.3	19.1	231.8	5.1	0.72
4	18.2	3.2	213.6	5.1	0.64
5	15.5	10.0	213.6	4.9	0.60
6	9.1	3.2	218.2	4.9	0.72
7	9.6	2.7	195.5	6.5	0.64
8	6.4	6.8	240.9	5.4	0.79
9	2.3	10.0	228.1	5.3	0.72
10	6.4	4.1	186.4	6.1	0.60
11	0.09	4.5	68.2	6.4	0.41
12	4.1	9.1	113.6	6.3	0.49
13	6.4	11.8	213.6	5.1	0.72
14	13.2	2.3	231.8	5.2	0.76
15	8.2	4.1	109.1	6.2	0.45
16	4.1	8.2	118.2	6.1	0.49
17	4.1	7.7	131.8	6.1	0.49
18	10.9	8.7	209.1	5.9	0.53
19	4.1	7.7	154.5	6.2	0.49
20	1.4	5.4	99.9	6.4	0.45
21	4.1	8.2	213.6	6.1	0.72
22	5.5	10.9	259.1	5.2	0.79
23	0.9	10.9	172.7	6.9	0.64
24	4.1	5.5	213.6	5.9	0.72
25	4.1	8.2	236.4	5.5	0.72
26	2.3	2.9	159.1	6.4	0.68
27	0.9	3.2	86.4	6.8	0.41
28	4.1	5.5	127.3	5.6	0.49
29	4.1	4.5	177.3	6.5	0.53
30	6.4	9.1	245.5	5.3	0.60
31	6.4	1.8	213.6	5.9	0.56
32	9.6	8.6	231.8	5.8	0.60
33	12.3	13.2	309.1	4.9	0.91
34	5.5	5.4	118.2	6.3	0.72
35	4.1	5.5	213.6	6.0	0.83
36	6.4	4.1	190.9	6.2	0.72
37	9.1	2.7	177.3	5.3	0.64
38	4.1	8.2	209.1	4.8	0.68
39	2.3	5.9	149.9	4.9	0.60
40	2.3	6.8	177.3	5.4	0.64

Contd.

Appendix-II(b). Continued

1	2	3	4	5	6
41	2.3	8.2	236.3	4.9	0.76
42	6.4	8.6	245.4	4.9	0.76
43	10.0	2.3	272.7	4.8	0.79
44	9.6	6.3	245.4	5.0	0.76
45	9.6	5.4	213.6	5.1	0.72
46	4.1	4.1	254.5	5.1	0.72
47	4.1	5.5	177.3	4.9	0.83
48	2.3	8.9	277.3	6.2	0.60
49	2.3	13.6	281.8	4.9	0.79
50	6.4	7.5	227.3	5.2	0.76
51	2.3	0.9	113.6	6.3	0.64
52	2.3	4.1	209.1	5.9	0.68
53	1.4	1.8	127.3	6.3	0.53
54	2.3	4.1	163.6	5.9	0.60
55	0.9	1.4	118.2	5.9	0.53
56	14.1	8.2	277.3	5.4	0.68
57	6.4	1.8	218.2	5.9	0.60
58	13.2	9.1	322.7	4.5	0.87
59	2.3	19.1	195.4	5.6	0.64
60	2.3	9.1	136.4	5.6	0.53
61	9.1	9.1	245.5	5.7	0.72
62	67.8	91.9	949.9	4.7	2.72
63	57.8	14.1	759.1	4.8	2.42
64	14.6	10.9	313.6	5.2	1.24
65	0.9	2.7	109.1	5.8	0.68
66	1.4	0.9	95.4	6.7	0.49
67	2.3	2.3	122.7	6.2	0.53
68	4.6	1.8	210.3	5.9	0.72
69	2.3	2.3	195.4	6.2	0.72
70	0.9	1.4	95.4	6.7	0.49
71	1.4	0.9	109.1	5.9	0.53
72	7.7	9.6	272.7	5.2	1.20
73	8.2	4.1	231.8	5.3	0.87
74	10.9	14.6	268.2	5.4	0.91
75	4.6	11.8	218.4	5.6	0.91
76	13.2	7.3	318.2	5.2	1.54
77	9.6	10.0	268.2	5.4	0.95
78	9.1	9.6	268.2	5.4	0.98
79	4.1	2.3	213.6	5.8	0.64
80	5.5	2.7	286.4	5.2	1.47
81	10.9	6.4	245.4	5.8	0.72
82	4.1	7.3	168.2	6.3	0.68
83	6.4	2.2	159.1	6.2	0.68

Contd.

Appendix-II(b). Continued

1	2	3	4	5	6
84	6.4	10.4	245.5	5.4	0.56
85	10.5	10.0	249.9	5.2	0.79
86	8.2	4.1	213.6	5.8	0.64
87	15.5	10.4	272.7	5.2	0.79
88	6.4	5.9	218.2	5.3	0.64
89	4.6	8.1	204.5	6.1	0.56
90	2.3	1.3	136.4	6.7	0.56
91	3.6	3.2	186.4	5.6	0.95
92	2.7	2.3	195.4	5.7	0.76
93	4.9	1.9	213.6	5.5	0.83
94	3.6	4.1	190.9	5.8	0.91
95	4.1	2.7	204.5	5.8	0.95
96	4.5	3.7	218.2	5.6	0.87
97	3.2	4.5	227.3	5.5	0.79
98	3.2	5.0	209.1	5.7	0.83
99	4.9	4.2	240.9	5.3	1.24
100	2.7	4.1	177.3	5.9	6.79
101	6.4	4.5	186.4	5.8	0.72
102	4.6	5.0	177.3	5.9	0.60
103	9.6	7.2	236.4	5.2	0.79
104	6.4	3.2	163.6	6.1	0.53
105	8.2	4.1	281.8	5.1	0.87

APPENDIX-III

Location from where soil was collected to conduct pot culture (Alluvial soil)

Location No.	Location	District	Available SO_4-S (ppm)
A.1	Chalakkudy (ARS)	Thrissur	6.4
A.2	Purakkattil padam	,,	6.4
A.3	Chalissery padam	Palakkad	8.2
A.4	Chuvannamannu padam	Thrissur	10.0
A.5	Padikkaparambu padam	Malappuram	23.2
A.6	Pullikanakku padam	Alappuzha	21.4
A.7	Anaparambal padam	,,	3.2
A.8	Alathoor	Palakkad	4.1
A.9	Chempuru	Thiruvananthapuram	2.3
A.10	Aruvikkara	,,	8.2
A.11	Athiannur	,,	12.3
A.12	Parasuvakkal	,,	15.5
A.13	Karamana	,,	6.4
A.14	Kayamkulam	Alappuzha	10.5
A.15	Valiakulangara	,,	6.4
A.16	Mannar	,,	2.3
A.17	Thazhava	Kollam	4.6
A.18	Erumayur	Palakkad	15.5
A.19	Kannara	Thrissur	15.5
A.20	Vazhukkampara	,,	8.2
A.21	Olavakkode	Palakkad	10.9
A.22	Palapatta	,,	17.3
A.23	Puthuppariaram	,,	14.1
A.24	Kulamkkanda	,,	9.1
A.25	Muttikulangara	,,	4.6
A.26	Valayakkadu	,,	4.6
A.27	Mullakkara padam	,,	10.0
A.28	Pottakkulam	,,	2.7
A.29	Kavalpattapadam	,,	10.5
A.30	Coyalmannam	,,	8.2

APPENDIX-IV

Locations from where soil was collected to conducting pot culture
(Brown hydromorphic soil)

Location No.	Location	District	Soluble SO_4-S (ppm)
B.1	Sankaramangalam	Palakkad	4.1
B.2	Puliyoor	Alappuzha	14.1
B.3	Vavannur	Palakkad	4.1
B.4	Koppam	,,	8.2
B.5	Vayakkal	Kollam	9.1
B.6	Vadanakkurichi	Palakkad	13.2
B.7	Pattambi	,,	6.4
B.8	Panniankara	,,	2.3
B.9	Puthoorkulam	,,	6.4
B.10	Chevakkodeu	,,	9.6
B.11	Vempalli	Kottayam	14.6
B.12	Ollookkara	Thrissur	12.3
B.13	Mannuthy SSF	,,	6.4
B.14	Thirumarady	Ernakulam	9.6
B.15	Vadakkancheri	Palakkad	9.1
B.16	Kainikattuthekkoottu padam	Thrissur	5.5
B.17	Mannuthy IF	,,	4.1
B.18	Erinjikulam padam	,,	4.1
B.20	Pampakkuda	Ernakulam	4.1
B.20	Anchalpetti	,,	4.1
B.21	Ottabekkaramangalam	Thiruvananthapuram	19.5
B.22	Perumpilavu	Thrissur	6.4
B.23	Dhoni	Palakkad	2.3
B.24	Nechupully	,,	6.4
B.25	Kannamkodu	,,	15.5
B.26	Cherianad	Alappuzha	6.4
B.27	Ayoor	Kollam	4.1
B.28	Nilamel	,,	5.5
B.29	Poomodupadam	Palakkad	22.3
B.30	Pandarakkadu padam	,,	18.2

APPENDIX-V(a)

Growth characters of rice plants under no sulphur and S @ 40 kg ha^{-1} in samples collected from alluvial soils

Location No.	Height of plants (cm)		Tiller per pot No.		Production tillers No. per pot		Score of green algae*
	S_O	S_{40}	S_O	S_{40}	S_O	S_{40}	
1	89	93	16	19	14	16	2.45
2	83	84	14	16	11	14	2.24
3	86	88	18	20	14	17	2.45
4	87	88	15	17	12	13	2.00
5	97	95	23	27	18	22	1.41
6	87	89	27	28	22	25	1.41
7	93	97	17	19	16	16	1.41
8	88	92	18	20	15	17	2.83
9	93	97	18	21	16	18	1.73
10	84	88	19	26	17	21	1.41
11	88	91	21	34	18	27	1.41
12	97	95	19	23	16	22	1.73
13	95	97	17	29	13	26	2.24
14	81	85	15	18	14	15	1.41
15	90	93	19	21	17	18	1.41
16	77	81	16	17	12	15	2.00
17	80	82	13	15	11	13	2.00
18	94	95	25	27	21	22	1.73
19	88	95	15	18	13	15	2.00
20	83	84	19	19	16	17	2.00
21	81	83	15	16	11	13	1.73
22	89	91	32	36	22	29	2.24
23	88	94	19	25	18	22	1.41
24	85	91	18	18	15	16	2.00
25	97	99	23	23	20	20	2.00
26	92	94	16	18	13	14	2.45
27	88	92	23	26	19	21	1.73
28	79	80	19	21	14	16	1.73
29	86	92	21	23	17	19	1.41
30	95	97	18	18	15	14	2.45

* after $\sqrt{x} + 1$ transformation

APPENDIX-V(b)

Yield of grain, straw and content of S in grain and straw of rice plants under S_0 and S_{40} levels (Alluvial soil)

Sample	Grain yield (g)		S content of grain(%)		Straw yield (g)		S content of straw (%)	
	S_O	S_{40}	S_O	S_{40}	S_O	S_{40}	S_O	S_{40}
1	15.41	18.85	0.0564	0.1009	15.22	18.84	0.0481	0.129
2	13.43	15.95	0.0519	0.0991	13.37	15.91	0.0581	0.1045
3	15.80	17.73	0.0920	0.1100	14.76	16.49	0.0485	0.129
4	13.50	14.35	0.0560	0.0993	13.82	15.93	0.0722	0.1396
5	18.46	18.10	0.1136	0.1119	19.06	19.06	0.1185	0.1591
6	18.10	18.73	0.0974	0.1129	19.79	22.19	0.1566	0.1918
7	17.10	17.35	0.1015	0.1403	14.98	15.99	0.1519	0.1553
8	16.23	19.10	0.0403	0.0870	14.31	18.36	0.0361	0.0965
9	12.30	15.53	0.0816	0.0922	16.20	18.97	0.0434	0.0925
10	15.28	16.40	0.0959	0.0982	15.71	15.66	0.0905	0.1555
11	18.23	19.48	0.0987	0.1049	18.97	19.03	0.0861	0.0972
12	20.58	20.48	0.0839	0.0890	20.40	22.08	0.0994	0.1049
13	15.88	17.75	0.0405	0.0868	18.65	19.99	0.0428	0.0787
14	10.10	10.58	0.0945	0.0977	11.32	12.05	0.0933	0.1541
15	13.13	13.83	0.0994	0.1066	13.55	21.05	0.0947	0.1468
16	10.33	14.30	0.0580	0.0935	13.33	14.35	0.0599	0.1236
17	12.60	14.88	0.0601	0.0964	12.33	14.07	0.0600	0.1085
18	19.05	19.77	0.0897	0.0961	19.66	20.21	0.0822	0.1001
19	12.45	13.33	0.0672	0.0961	12.16	12.21	0.0674	0.0969
20	8.15	9.60	0.0721	0.0912	7.81	10.05	0.1381	0.1664
21	9.18	9.73	0.0871	0.0994	9.64	9.99	0.1106	0.1713
22	18.03	18.46	0.0627	0.0880	23.89	24.35	0.0694	0.0892
23	9.43	10.65	0.0500	0.0950	9.47	11.16	0.0512	0.1420
24	15.00	17.35	0.0816	0.0982	14.37	16.20	0.0792	0.0862
25	13.03	15.13	0.0550	0.1060	12.59	14.82	0.0592	0.1120
26	9.85	11.33	0.0450	0.0950	10.41	11.24	0.0484	0.1416
27	13.68	14.35	0.0860	0.0950	13.14	13.52	0.0848	0.0950
28	8.75	11.60	0.0720	0.0945	11.12	12.73	0.0717	0.1033
29	12.68	13.93	0.0910	0.0944	13.11	13.16	0.0839	0.0954
30	11.18	13.65	0.0410	0.0818	10.33	16.49	0.0366	0.0857

APPENDIX-V(c)

Plant nutrient contents in rice (S_O - control) of pot culture

Alluvial soil

Sample No.	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	Zn (ppm)	Mn (ppm)	Cu (ppm)
A.1	0.63	0.125	2.175	0.68	0.278	33.7	28.9	10
A.2	0.77	0.138	2.20	0.61	0.273	56.8	26.5	10
A.3	0.98	0.150	2.325	0.73	0.275	32.7	57.6	39
A.4	1.19	0.169	2.425	0.92	0.288	26.7	57.4	7
A.5	1.26	0.238	2.85	0.61	0.272	30.2	43.7	7
A.6	1.12	0.194	2.425	0.28	0.232	30.7	42.0	7
A.7	1.19	0.213	2.65	0.30	0.272	62.8	56.7	14
A.8	0.70	0.125	2.275	0.38	0.253	38.7	81.4	9
A.9	0.63	0.125	2.250	0.48	0.262	39.2	144.2	9
A.10	1.12	0.163	2.60	0.56	0.267	19.6	149.0	8
A.11	1.05	0.206	2.65	0.82	0.275	32.9	135.5	7
A.12	1.24	0.225	2.75	0.57	0.267	43.3	100.1	6
A.13	0.85	0.175	2.350	0.58	0.273	10.1	112.9	17
A.14	1.12	0.188	2.65	0.59	0.271	40.8	47.6	13
A.15	1.19	0.213	2.65	0.42	0.274	66.1	35.2	8
A.16	0.49	0.125	.225	0.53	0.273	34.8	17.4	7
A.17	0.56	0.150	2.275	0.65	0.271	31.5	32.0	7
A.18	1.05	0.213	2.58	0.56	0.274	32.2	125.5	7
A.19	1.12	0.206	2.50	0.67	0.277	48.3	49.0	9
A.20	0.56	0.156	2.275	0.70	0.280	8.2	168.3	5
A.21	1.12	0.194	2.55	0.40	0.250	60.5	40.2	11
A.22	1.26	0.213	2.65	0.46	0.276	12.5	203.5	6
A.23	1.19	0.206	2.65	0.44	0.270	48.9	168.4	30
A.24	0.77	0.138	2.300	0.57	0.268	44.8	118.1	8
A.25	0.84	0.181	2.275	0.52	0.271	47.0	140.0	8
A.26	0.91	0.194	2.375	0.39	0.263	71.9	103.0	11
A.27	1.19	0.213	2.65	0.62	0.251	60.0	143.3	8
A.28	0.63	0.181	2.175	0.54	0.253	60.5	63.7	61
A.29	1.12	0.206	2.50	0.47	0.269	42.4	97.4	8
A.30	0.49	0.125	2.125	0.49	0.264	52.5	48.8	8

APPENDIX-VI(a)

Growth characters of rice plants under no sulphur and S @ 40 kg ha^{-1} in samples colleted from brown hydromorphic soils

Soil samples	Height of plants (cm)		Tillers per pot No.		Productive tillers No.		Score of green algae
	S_0	S_{40}	S_0	S_{40}	S_0	S_{40}	
B.1	95	94	15	16	13	15	1.73
B.2	94	96	15	17	15	14	1.41
B.3	94	95	22	24	16	18	1.73
B.4	88	95	19	19	14	15	2.00
B.5	83	84	19	21	15	18	1.73
B.6	91	93	18	19	16	16	1.41
B.7	98	99	17	18	14	15	2.24
B.8	91	95	18	19	14	17	2.00
B.9	88	98	19	22	17	20	2.00
B.10	99	102	15	18	12	14	2.00
B.11	97	92	24	28	20	21	1.73
B.12	93	95	19	21	18	17	2.00
B.13	88	94	17	20	13	17	1.24
B.14	91	98	18	22	14	18	1.41
B.15	93	98	20	26	17	20	1.41
B.16	95	97	19	20	16	17	2.24
B.17	88	91	15	18	13	15	2.24
B.18	89	94	17	20	14	17	2.65
B.19	89	93	16	18	13	14	2.24
B.20	79	91	14	16	12	13	2.24
B.21	92	94	16	18	13	15	1.41
B.22	74	82	15	17	11	13	1.73
B.23	81	87	17	19	13	15	2.24
B.24	80	85	16	18	12	13	1.73
B.25	88	92	23	25	18	20	1.73
B.26	85	87	17	22	15	17	1.73
B.27	78	83	16	18	13	14	2.00
B.28	83	86	19	19	14	17	2.24
B.29	79	93	18	24	17	21	1.41
B.30	83	91	23	24	19	20	1.41

APPENDIX-VI(b)

Yield of grain and straw and content of S in grain and straw of rice plants under S_O and S_{40} levels (Brown hydromorphic soil)

Sample No.	Grain yield (g)		S content of grain(%)		Straw yield (g)		S content of straw(g)	
	S_0	S_{40}	S_0	S_{40}	S_0	S_{40}	S_0	S_{40}
B.1	8.65	9.40	0.0843	0.0972	8.03	8.78	0.0867	0.1217
B.2	9.80	9.78	0.0902	0.0969	10.38	10.85	0.0945	0.1203
B.3	10.13	11.00	0.0821	0.0836	8.64	10.21	0.0803	0.1165
B.4	9.95	10.5	0.0857	0.0936	10.2	11.89	0.0702	0.1111
B.5	9.35	10.5	0.0691	0.0892	9.6	11.55	0.0804	0.0967
B.6	10.16	10.65	0.0940	0.1068	10.41	10.67	0.1214	0.1548
B.7	10.80	12.53	0.0567	0.0894	11,16	14.35	0.0534	0.0885
B.8	9.93	11.35	0.0705	0.0970	10.6	11.85	0.0734	0.1263
B.9	11.85	12.83	0.0821	0.0907	12.34	14.23	0.0841	0.1203
B.10	10.50	11.73	0.0742	0.0924	12.41	13.51	0.0710	0.1049
B.11	14.35	14.38	0.0912	0.0938	15.08	15.89	0.0817	0.0930
B.12	10.00	12.03	0.0746	0.0882	9.92	12.26	0.0793	0.1075
B.13	10.53	13.85	0.0550	0.0873	11.09	14.91	0.0534	0.1291
B.14	14.08	15.00	0.0580	0.0930	15.19	15.49	0.0965	0.1115
B.15	9.98	12.25	0.082	0.0994	10.78	12.36	0.0945	0.1328
B.16	15.14	16.13	0.0880	0.0888	12.90	13.99	0.0530	0.0991
B.17	14.21	16.01	0.0737	0.0737	13.37	16.27	0.0537	0.1064
B.18	17.25	20.70	0.0420	0.0859	14.18	16.15	0.0392	0.0999
B.19	13.35	16.16	0.0470	0.0956	11.93	14.81	0.0522	0.1175
B.20	13.30	15.60	0.0470	0.0965	12.54	14.91	0.0443	0.1080
B.21	15.65	18.00	0.0801	0.0970	14.87	17.11	0.0922	0.1217
B.22	9.8	10.7	0.0920	0.1033	8.21	11.11	0.0943	0.1102
B.23	6.9	10.0	0.0419	0.0878	7.35	10.68	0.0425	0.1192
B.24	10.69	12.80	0.0612	0.0905	11.65	12.16	0.0611	0.0995
B.25	13.20	13.18	0.0829	0.0960	13.23	13.65	0.0829	0.1117
B.26	15.39	18.65	0.0761	0.0933	15.81	15.94	0.0785	0.0919
B.27	9.63	11.43	0.0689	0.0886	10.51	12.10	0.0709	0.0861
B.28	11.13	13.53	0.0464	0.0968	11.33	12.92	0.0502	0.1107
B.29	13.70	13.40	0.0912	0.1030	12.20	13.05	0.0904	0.1008
B.30	13.58	13.45	0.0921	0.0980	12.92	14.39	0.0919	0.1055

APPENDIX-VI(c)

Plant nutrient contents in rice (S_0 - control) of pot culture

Brown hydromorphic soil

Sample No.	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	Zn (ppm)	Mn (ppm)	Cu (ppm)
B.1	1.05	0.231	2.55	0.45	0.264	63.9	165.3	17
B.2	1.26	0.250	2.75	0.53	0.276	70.2	102.1	21
B.3	0.98	0.225	2.25	0.51	0.272	38.2	80.7	14
B.4	1.05	0.175	2.475	0.60	0.289	48.2	131.2	9
B.5	0.84	0.138	2.175	0.63	0.265	47.7	133.2	8
B.6	1.19	0.181	2.700	0.48	0.273	35.8	95.8	13
B.7	0.70	0.138	2.150	0.34	0.261	31.9	220.8	11
B.8	0.84	0.163	2.225	0.51	0.276	35.0	115.6	46
B.9	0.98	0.169	2.400	0.44	0.272	26.1	128.5	15
B.10	0.63	0.175	2.475	0.48	0.267	43.9	96.3	14
B.11	1.12	0.213	2.800	0.44	0.248	37.2	76.5	11
B.12	0.63	0.163	2.150	0.36	0.270	57.1	141.6	16
B.13	0.49	0.125	2.05	0.45	0.253	24.4	143.6	13
B.14	1.19	0.194	2.65	0.43	0.259	25.7	270.2	15
B.15	0.63	0.131	2.225	0.61	0.275	47.9	63.4	11
B.16	1.05	0.176	2.475	0.39	0.213	32.5	333.1	9
B.17	0.70	0.131	2.225	0.37	0.231	20.2	325.9	8
B.18	0.84	0.131	2.200	0.36	0.232	23.9	282.3	41
B.19	0.77	0.125	2.100	0.35	0.256	32.1	374.9	10
B.20	0.84	0.125	2.125	0.36	0.254	34.3	359.1	11
B.21	0.91	0.125	2.375	0.28	0.236	46.5	262.4	9
B.22	0.70	0.150	2.125	0.65	0.276	53.2	40.5	23
B.23	0.49	0.144	2.025	0.46	0.274	58.8	104.6	9
B.24	0.98	0.175	2.400	0.42	0.262	46.4	90.0	8
B.25	1.26	0.238	2.850	0.40	0.246	19.5	89.6	6
B.26	0.98	0.200	2.475	0.28	0.238	62.0	59.8	10
B.27	0.91	0.156	2.350	0.56	0.269	40.9	87.5	14
B.28	0.91	0.138	2.350	0.38	0.250	48.2	111.7	12
B.29	1.26	0.244	2.850	0.41	0.274	54.3	111.7	10
B.30	1.19	0.213	2.750	0.37	0.231	32.7	337.7	23

APPENDIX-VII

Physico-chemical properties of the field experiment sites

No.	Particulars	Alluvial soil		Brown hydromorphic	
		Kharif plot Plot 1	*Rabi* plot Plot 2	*Kharif* plot Plot 3	*Rabi* plot Plot 4
A.	Mechanical Composition				
	Course sand (%)	25.2	24.9	23.2	27.4
	Fine sand (%)	23.9	24.5	23.1	25.6
	Silt (%)	23.4	22.8	23.2	24.2
	Clay (%)	27.5	27.8	25.5	25.8
B.	Chemical composition				
	Organic carbon	0.68	0.62	0.50	0.41
	Total Nitrogen (%)	0.156	0.148	0.138	0.132
	Available P (kg ha^{-1})	46.25	38.65	34.52	33.75
	Available K (kg ha^{-1})	320	286	318	299
	Available S (ppm)	6.4	8.2	3.2	4.9
	pH	5.9	5.7	6.1	6.4
	Calcium (%)	0.65	0.59	0.92	0.91
	Magnesium (%)	1.48	1.22	1.42	1.58
	Zinc (ppm)	247	231	106	109
	Manganese (ppm)	9266	8686	12688	13252
	Copper (ppm)	92	88	24	36
	Iron (ppm)	335	308	385	409

Particulars	Method employed
Organic carbon	Walkley and Black method
Total Nitrogen	Semimicro-kjeldahl method
Available P	Bray I extractant, molybdophosphoric acid method
Available K	Neutral normal Am. Acetate extractant flame photometry
Available S	$CaCl_2$ extractant, turbidimetry
pH	1:2.5 soil water suspension (pH meter)
Calcium	Atomic Absorption Spectrophotometer
Magnesium	,,
Zinc	,,
Manganese	,,
Copper	,,
Iron	Acetate buffer

APPENDIX-VIII

Weather during the cropping period 1992-93

Period (Date and week end)	Standard week	CSRC, Karamana (Alluvial)			RARS, Pattambi (Brown hydromorphic)		
		Rainfall (mm)	Temperarture °C Max.	Min.	Rainfall (mm)	Temperature °C Max.	Min.
Kharif							
July 1	26				177	30.3	22.7
8	27				65	30.4	22.8
15	28	20	29.6	22.6	29	29.6	22.2
22	29	60	28.1	22.9	304	28.2	21.7
29	30	106	29.1	23.0	274	28.2	22.0
Aug 5	31	42	28.6	22.4	204	27.7	21.8
12	32	31	29.0	23.3	102	29.3	22.3
19	33	17	29.7	23.9	101	29.0	22.6
26	34	1	30.6	23.7	34	29.9	22.5
Sept 2	35	43	28.7	23.3	91	29.1	22.4
9	36	13	29.4	23.4	75	29.0	22.0
16	37	15	29.9	23.7	25	30.5	21.9
23	38	2	31.7	23.9	3	32.0	23.1
30	39	10	30.6	23.4	163	30.2	22.4
Oct 7	40	94	29.6	22.7	93	30.5	21.6
14	41	226	28.9	23.4	-	-	-
Rabi							
Nov 11	45				37	31.8	21.6
18	46				277	30.2	21.9
25	47	31.0	30.9	23.0	14	31.5	21.3
Dec 2	48	15.0	31.3	23.1	0	32.2	20.7
9	49	8.0	31.4	22.9	0	31.8	20.9
16	50	7.0	31.7	23.0	0	31.4	19.4
23	51	18.0	32.9	22.9	0	31.7	20.9
31	52	0	32.1	20.9	0	31.1	17.0
Jan 7	1	0	32.0	20.4	0	32.0	18.8
14	2	0	31.3	21.7	0	32.5	18.9
21	3	0	30.9	21.4	0	32.6	16.3
28	4	0	32.1	22.4	0	32.4	20.2
Feb 4	5	0	31.9	21.6	0	33.9	20.2
11	6	0	32.1	21.4	0	34.9	19.6
18	7	0	32.4	23.3	0	34.8	21.3
25	8	4	32.1	23.6	0	-	-
Mar 4	9	0	32.0	23.3	-	-	-

CSRC, Karamana

Kharif	Date of transplanting	9.7.92
	Date of harvest	12.10.92
Rabi	Date of transplanting	25.11.92
	Date of harvest	4.3.93

RARS, Pattambi

Kharif	Date of transplanting	1.7.92
	Date of harvest	5.10.92
Rabi	Date of transplanting	9.11.92
	Date of harvest	12.2.93

STATUS AND AVAILABILITY OF SULPHUR IN THE MAJOR PADDY SOILS OF KERALA AND THE RESPONSE OF RICE TO SULPHATIC FERTILIZERS

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ABSTRACT OF A THESIS

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ABSTRACT

A series of investigations were undertaken entitled "Status and availability of sulphur in the major paddy soils of Kerala and the response of rice to sulphatic fertilizers" at College of Horticulture, Kerala Agricultural University, Vellanikkara from 1990 to 1994 with the objectives: (i) to assess the sulphur status of major paddy soils of Kerala (viz. alluvial and brown hydromorphic) (ii) to identify an appropriate soil test procedure for estimation of available sulphur in these soils (iii) to determine the critical levels of sulphur in the soils and plant (iv) to study the response of rice to two popular sulphatic fertilizers of Kerala (viz. ammonium sulphate and ammonium phosphate sulphate) and (v) to assess the sulphur use efficiency of ^{35}S labelled ammonium sulphate and ammonium phosphate sulphate.

The studies were conducted in four parts. In Part I of the studies, 105 samples each from alluvial and brown hydromorphic soils were collected from 10 rice growing districts of Kerala based on area under rice crop, estimated soluble SO_4-S, adsorbed SO_4-S, total sulphur content and organic + non sulphate sulphur contents. The soils were classified in to categories of low, medium and high based on the available SO_4-S extracted by $CaCl_2$. From this part of the study it was found out that 56 per cent of alluvial soils and 83 per cent of brown hydromorphic soils were deficient in sulphur. Sulphur deficient locations and sulphur sufficient locations were delineated. Sulphur status map for rice soils of Kerala was prepared.

In Part II, representative soils belonging to three status categories (low, medium and high) were collected from 30 locations each of alluvial and brown hydromorphic types and conducted a pot culture with two treatments (S_0 and S_{40} kg S ha^{-1}) with two replications. These soils were analysed with 12 methods of sulphur estimation using different extractants. The relative yield of grain, straw and total biomass and relative uptake of nutrient S were estimated. Correlations between different extractants were worked out. Correlations between relative yields and sulphur extracted by different methods were studied. From this the suitability of the methods were evaluated. It was found that all the 12 methods studied could extract available SO_4-S satisfactorily.

Scatter diagrams were drawn with relative yields of grain, straw, biomass and uptake of S against the sulphur extracted by different extractants. The critical levels were worked out following the Cate and Nelson procedure. The best suitable extractants for the estimation of sulphur in alluvial soil and brown hydromorphic soil were found out by assessing the responsiveness of rice in soils classified as deficient by each extractant. It was observed that in alluvial soil the critical levels varied between 5 to 22 ppm for different extractants. Monocalcium phosphate was found to be the best extractant for alluvial soils. In brown hydromorphic soil the critical levels varied between 6 ppm to 20 ppm. Monocalcium phosphate + acetic acid was found to be the best extractant for brown hydromorphic soils.

Relationship between plant content of S and relative yield of grain studied by Cate and Nelson procedure showed that in alluvial soil 0.075 per cent S and in brown hydromorphic soil 0.08 per cent S in plant at harvest were critical concentrations below which response to applied sulphur can be expected.

In Part III of the studies, two locations having sulphur deficiency, one each falling under alluvial and brown hydromorphic soil, were selected for field experiments (CSRC, Karamana - alluvial and RARS, Pattambi - brown hydromorphic). Field experiments were conducted in these two locations for two seasons (*Kharif* and *Rabi* 1992-93) with nine treatments (control - S_0, 4 levels of ammonium sulphate - S_{10}, S_{20}, S_{30} and S_{40} and 4 levels of ammonium phosphate sulphate - S_{10}, S_{20}, S_{30} and S_{40} kg S ha^{-1} in 2 x 4 + 1 factorial RBD with 3 replications). The results revealed that sulphur levels significantly increased yield of grain and straw and growth attributes like productive tillers. Sink capacity and dry matter production were increased by sulphur application. Among the two sources ammonium phosphate sulphate was found to be superior to the other. Agronomic efficiency, physiological efficiency and apparent recovery efficiency showed that the efficiencies were maximum at low level of sulphur (10 kg S ha^{-1}). Sulphur levels increased, S, N and K uptake. The ratios of nutrients removed per ton showed that the ratios of these nutrients to sulphur narrowed down with sulphur application over control. The gross income, net income and B : C ratio were higher for sulphur application and the highest values were for 30 kg S ha^{-1}. The physical optimum levels ranged between 25.34 to 31.47 and economic optimum levels ranged between 23.06 and 28.73 for the sources in two locations at the two seasons. The economic optimum levels of AS and APS were 27 and 25 kg S ha^{-1} respectively. There was no residual effect in general, except that at brown hydromorphic soil sulphur @ 40 kg ha^{-1} could contribute to meet the requirement of sulphur for the succeeding crop in producing more grain yield.

In Part IV of the studies, a pot culture experiment with ^{35}S labelled AS and APS was conducted at Radiotracer lab. The radioassay and chemical analysis were conducted. The soils and levels of S were same as that of field experiment.

The specific activity of grain and straw increased with higher levels of ^{35}S application. The sulphur use efficiency in alluvial soil was highest at sulphur rate of 20 kg S ha^{-1}. In brown hydromorphic soil sulphur use efficiency was highest at 30 kg S ha^{-1}. Sulphur taken up from fertilizer significantly increased with sulphur levels in both the soils. A-values were on par for different levels in both the soils. Brown hydromorphic soil showed higher A-value, sulphur use efficiency and total sulphur taken up from fertilizer.