CATEGORIZATION OF DISTRICTS BASED ON NON-EXCHANGEABLE POTASSIUM: GENERATION GIS MAPS AND IMPLICATIONS IN EFFICIENT K FERTILITY MANAGEMENT IN INDIAN AGRICULTURE

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ABSTRACT

Potassic fertilizer recommendations are made based on available (exchangeable + water soluble) K status of soils in different soil testing laboratories in India. However, recent studies employing a variety of measures of nonexchangeable K indicated a very substantial contribution of nonexchangeable fraction of soil K to crop K uptake. Present paper examines the information generated in the last 30 years on the status of nonexchangeable K in Indian soils, categorization of Indian soils based on exchangeable and nonexchangeable K fractions based on GIS mapping and K recommendations considering both the fractions of soil K. Inclusion of nonexchangeable K in the soil testing aids in predicting immediate K needs of crop plants as well as long term K needs of intensive cropping systems. Based on GIS based soil K fertility maps were prepared considering both exchangeable and nonexchangeable K, K deficient districts of the country were identified where K application is a must. Some maintenance dose of K is required in some districts where, exchangeable K is high but nonexchangeable K is low or medium. These GIS-based maps and suggested recommendations help to prioritize the K efficient zones where K application is essential and higher possibility exists for improving the K use efficiency. Special care should be taken on K fertilization on high K requirement crops like banana, sugarcane, potato, cotton, several cereals, tobacco, intensive fodder systems, vegetables and fruit crops, as these crops need regular K additions even when soils are in medium to high category. Therefore, inclusion of nonexchangeable K as a soil test in the soil testing laboratories for assessing long term K supplying capacity of Indian soils under intensive cropping systems and arriving at reliable K fertilizer recommendations is essential.

“Keywords:” GIS based soil K fertility maps, K recommendations, Verification, Crop responses.

INTRODUCTION

A significant proportion of plant needs of potassium (K) are met from nonexchangeable fraction of soil K (Srinivasarao et al., 1998a, 1998b, 1999, 2000, 2001, 2004). Under intensive cropping, in the absence of K fertilization, initially exchangeable K in soil contributes to plant K nutrition, but with further cropping exchangeable K attains a certain minimal level, then after, plant K removal from soil and contribution of nonexchangeable K to K uptake are almost synonymous and accounts for up to 90-95% of the total plant K uptake (Swarup and Srinivasarao, 1999; Srinivasarao et al., 2007b, 2010). Due to larger contribution of nonexchangeable K to plant K needs, lack of crop responses to applied K have been reported even in soils with low exchangeable K. The major sources of nonexchangeable K in soils are K rich 2:1 clay minerals such as micas and vermiculite (Mengel and Busch, 1982; Sparks and Huang, 1985; Mengel and Uhlenbecker, 1993; Srinivasarao et al., 2006b). However the release of K from the interlayer of these minerals may be very slow process depending upon the weathering stage of these minerals, and therefore, whether the K release rates of soils under cropping are in tune with plant K needs becomes the most important aspect as far as K nutrition of crop plants is concerned (Srinivasarao et al., 1997c; 1998b; 2007a).

India has 182 million ha cultivable land with 142.1 million ha net area sown and 121 million farmers. Among the states, Rajasthan has the largest portion of cultivable land followed by Maharashtra, Uttar Pradesh, Madhya Pradesh, Andhra Pradesh, Karnataka and Gujarat. The earlier estimates of soil fertility for K based on data generated from soil testing laboratories in the country indicated discrepancies in the percentage of samples testing high, though the overall soil K fertility of soils declined (Ghosh, 1976; Sekhon et al., 1992; Subba Rao et al., 1996). Besides, existing categorization of soils based on available K status is not able to explain the crop response pattern in many regions of India. Therefore, it has become essential to look into soil dynamics under intensive production systems and confirm which K fraction in soil is predominantly contributing to crop K nutrition (Subba rao, 1993; Srinivasarao et al., 2000). It was also essential to examine whether imported K fertilizer is efficiently used in Indian agriculture and whether it is applied to right crop on right soil, where K application is a must.

It is worthwhile to note that even the most progressive and productive states like Punjab and Haryana, have most skewed N: P2O5: K2O ratios. The focus has been on nitrogen followed by phosphorus and very little use of potassium resulting in a huge imbalance. In the year 2020, the deficit of K in Indian agriculture is projected to be around 10 million tonnes/annum while the estimates of N and P balances are positive (Srinivasarao and Khera, 1994a; 1994c; Srinivasarao et al., 2001a). There is obviously an urgent need for delineating the K deficient regions of the country district wise and asses the expected responses to applied K so that the K fertilizer management can be taken up with emphasis on efficient use of K and the consequent economy in K use (Srinivasarao et al., 2001a).

GIS Use in Agriculture

Geographical information systems offer the flexibility to visualize the spatial information in an easier way. With the availability of open source geographic information system software and high end computing facilities at low cost, use of GIS for scientific and utilities management has increased substantially. The GIS consists of organizing the information of an attribute in systematic continuous grids popularly known as raster maps or in continuous polygon (vector maps). Some of the important parameters for which public domain datasets available include weather parameters such as precipitation, temperature, wind speed etc and soil parameters such as field capacity, available water etc., on a grid basis at an interval of 0.25^{o}-0.5^{o} or higher (Siebert, 2007; Global soil data task group, 2000; IMD, 2005). Similarly datasets are available on polygons covering administrative boundaries such as country, state, district or on watershed/river basin scales. These vector maps helps the users to visualize the spatial variability over a region of interest for the specified attribute such as average annual rainfall across different districts in a state or available fertilizers etc. Administrative units such as districts were prioritized for research purpose based on the area under the crop, production and type of field based interventions such as water conservation, new variety introduction, pest and disease control measures etc., for rainfed cropping systems (covering rainfed rice, continuous cereals, cotton, oilseeds) in India. Similarly, sub district level areas were identified for cultivation of crops such as cotton and maize based on a crop suitability criteria covering major climatic (rainfall, temperature, relative humidity etc.) and soil parameters (soil texture, drainage, depth etc.) by merging them in GIS framework (NAIP report, 2005; CRIDA, 2004)

K Fertilizer Use in India

Two most important K fertilizers are potassium chloride or muriate of potash (MOP) containing 60% K_2O and sulphate of potash (SOP) containing 50% K_2O. India has no deposits of K fertilizers and all of it has to be imported. During 2008-09, 2.6 million tonnes (Mt) of K_2O (equivalent to 4.4 Mt MOP) was consumed in India and by 2025 the amount of K_2O consumption may double to meet the food grain needs of the country. However, the major concern is the spiraling international price of MOP; it was US$ 172 per tonne (fob Vancouver) in January 2007 and rose to US $405-625 per tonne in June 2008 and it is still on the rise. Currently the Government of India, spending about Rs 16300 crores ($ 3543 millions) annually, supplies the imported K fertilizer to farmers on subsidy. This scenario underlines the need for using the costly K fertilizer judiciously and most economically considering the crop K needs and the soil K reserves (Srinivasarao et al., 2000a).

Interpretation of available K in relation to nonexchangeable K in soil

Usually soils analyzing less than 50 mg kg^{-1} are rated low in available K, between 53 and 125 mg kg^{-1} K medium and above 125 mg kg^{-1} K as high in available K (Muhr et al., 1965). Unfortunately, these rating limits are irrespective of crops or soils. Solankey et al. (1992) studied the response of two wheat varieties to potassium on farmers' fields in swell-shrink soils. Though these soils were adequate in available K, crop responded to 13 mg ha^{-1}. They have established a critical limit of 6.2 mg ha^{-1} water-soluble K but failed to establish a critical limit based on ammonium acetate K. For delineation of fertility status, to isolate responsive soils from non-responsive ones and to recommend fertilizer K, critical limits for different crops in soils of various agro ecological regions are needed. Information is provided critical limits of available K in different crops on some well-defined soils. The data show a great diversity in the critical limits ranging from 48 to 137 mg kg^{-1} soil. These results also indicate that for single crop, there is wide range of critical limits. For example, for rice, the critical limits based on available K varied from 58 to 190 mg kg^{-1} and for sorghum from 240 to 335 mg kg^{-1}. Though crop requirements are fairly uniform across the regions, critical limits changed among soil types. It means that, crop K requirement are fulfilled from not only available K but also soil reserve K, which is not accounted now in soil test based K recommendations (Srinivasarao et al., 1995a).

Substantial contribution of nonexchangeable K to plant K uptake

The contribution of nonexchangeable K to plant K uptake was worked out in both green house studies as well as in field experiments. It was indicated that the crops particularly cereals with well branched root system draw K from soil, majorly from nonexchangeable source. The contribution of nonexchangeable K from eight illitic soils during 245 days of exhaustive cropping with sudangrass was 70% in first harvest (during initial 35 days) and it reached the highest level of 90% between 2nd and 4th harvests when exchangeable K attained minimal level (Srinivasarao et al., 1997b; Srinivasarao et al., 1998a; Srinivasarao et al., 2000b). After reaching the minimal level of exchangeable K, the pattern of crop K uptake and release of nonexchangeable K was almost identical (Srinivasarao et al., 2000c). Other studies have shown substantial contribution of nonexchangeable K to crop nutrition in illite-dominant alluvial soils to the extent of 80-90% of K uptake by crop. In a field experiment, Srinivasarao et al., 1998a; 2006a, showed that if only contribution from surface soils (0-15 cm) was taken into account, then the contribution of nonexchangeable K in plant K uptake by maize and pearlmillet varied from 77.5-88.9% whereas if the contribution from 60 cm of soil was included, the nonexchangeable K contribution came down to the range to 54-76%**.**

However when the same soil was employed in a green house study, the contribution extended to 89% in both maize and bajra. Studies also showed that contribution of nonexcheangeable K to crop removal decreased with increase in the level of applied K in wheat-sorghum (fodder) system on an alluvial soil.

Srinivasarao et al. (2000) reported that wheat crop utilized about 86% of the total K uptake from nonexchangeable source. But this contribution was reduced to negligible level when K fertilizer was applied**.** At higher levels of K application, there was a build up in the nonexchangeable K. In the case of pearlmillet, when no K was applied, the crop utilized about 95% of the K from nonexchangeable source and hence caused its decrease to 59% at 53.5 mg K kg^{-1} soil and to 13 and 22% at 107 and 160.5 mg K kg^{-1} levels, respectively**.** The nonexchangeable K utilized by the rice plant grown in pots in the green house ranged from 40.8 to 95.2% under exhaustive cropping and when K fertilizer was applied the K utilized by rice from nonexchangeable source was found reduced (Srinivasarao et al., 2000). To an alfalfa crop when more potassium was applied through fertilizers, less potassium was released from nonexchangeable source. The literature cited above clearly brought out that especially in soils containing good amounts of micaceous minerals, the nonexchangeable content of the soils should duly be taken into account while recommending K fertilizer rates. The fertilizer rates to be applied get reduced in proportion to the amount of nonexchangeable K in micaceous minerals.

Geographical Information System (GIS) based maps for Exchangeable K and Nonexchangeable K

Geographic information systems (GIS) was used for categorizing Indian districts into low, medium and high in terms of exchangeable and nonexchageable K based on published information on K status in Indian soils during last 30 years, across districts and tried to derive the patterns or relation of the same with reference to AERs, AESR maps (NBSS& LUP, Nagpur)(Sehgal et al., 1992). Using Arcview 3.1, district wise maps of exchangeable and nonexchangeable K and boundaries of agro ecological regions on these maps were imposed.

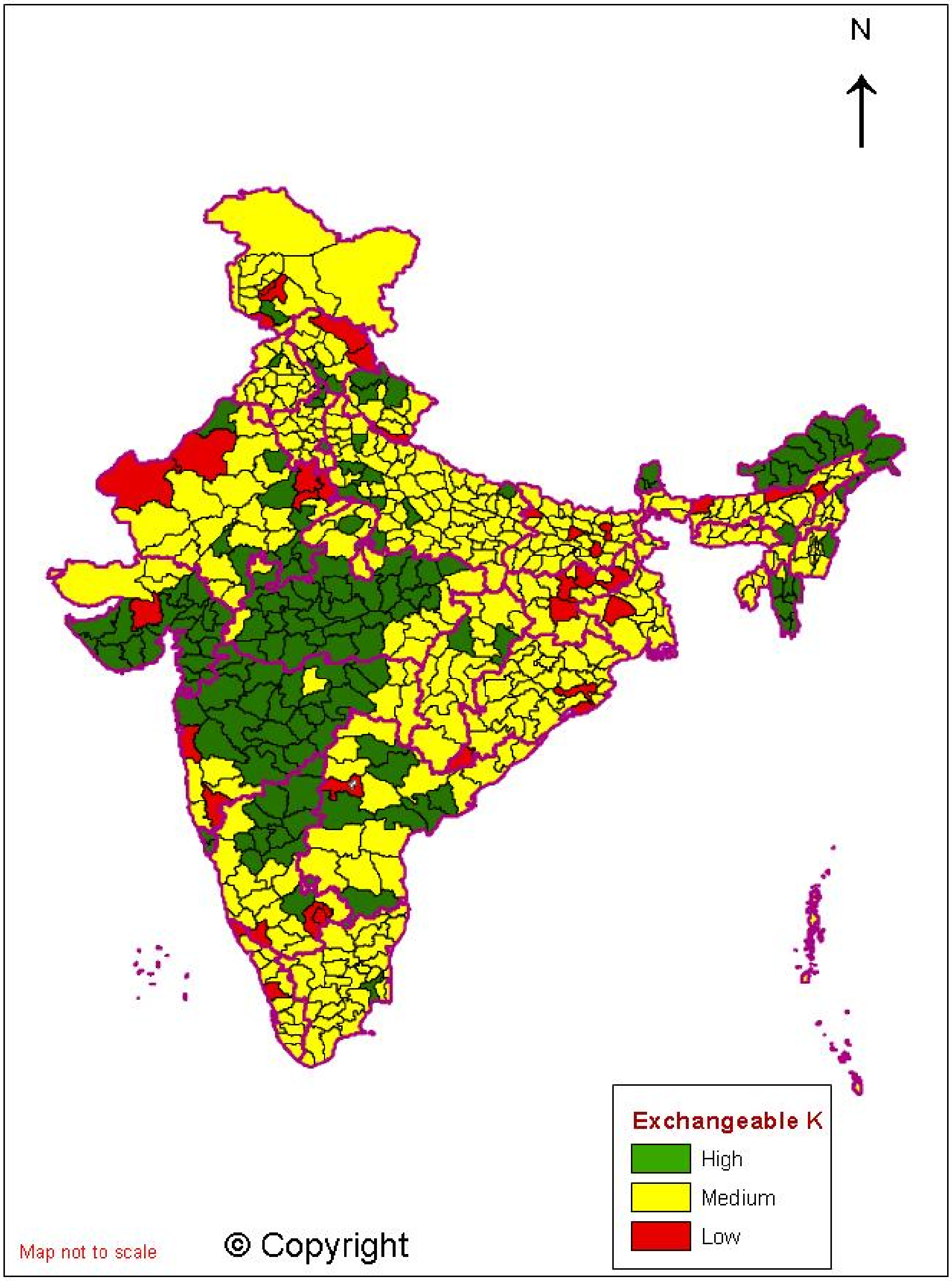
Categorization of districts as per their K reserves and availability

Data for exchangeable and nonexchangeable potassium (K) (mg kg^{-1}) of different soil groups of various regions in India were obtained in excel tabular format. A new field "District id" for each region is added to the tables and converted into "dbf format" compatible for Arcview GIS and saved. The resulting tables were added to Arcview tables and linked to the table of Districts shape file using common field "Districts id". The districts were classified into three categories low, medium and high by taking exchangeable K and nonexchangeable K as fields of classification as per the criteria given below. For deriving the maps for AESR and AERs for exchangeable K and nonexchangeable K, weighted average approach was followed for deriving a single unit value for the whole sub region, region as the case may be by unioning the maps of districts with sub region/region. For categorizing soils for exchangeable K three levels were used viz., low (<50 mg kg^{-1}), medium (50-120 mg kg^{-1}) and high (>120 mg kg^{-1}). For nonexchangeable K, the categories used were low (<300 mg kg^{-1}), medium (300-600 mg kg^{-1}) and high (>600 mg kg^{-1}).

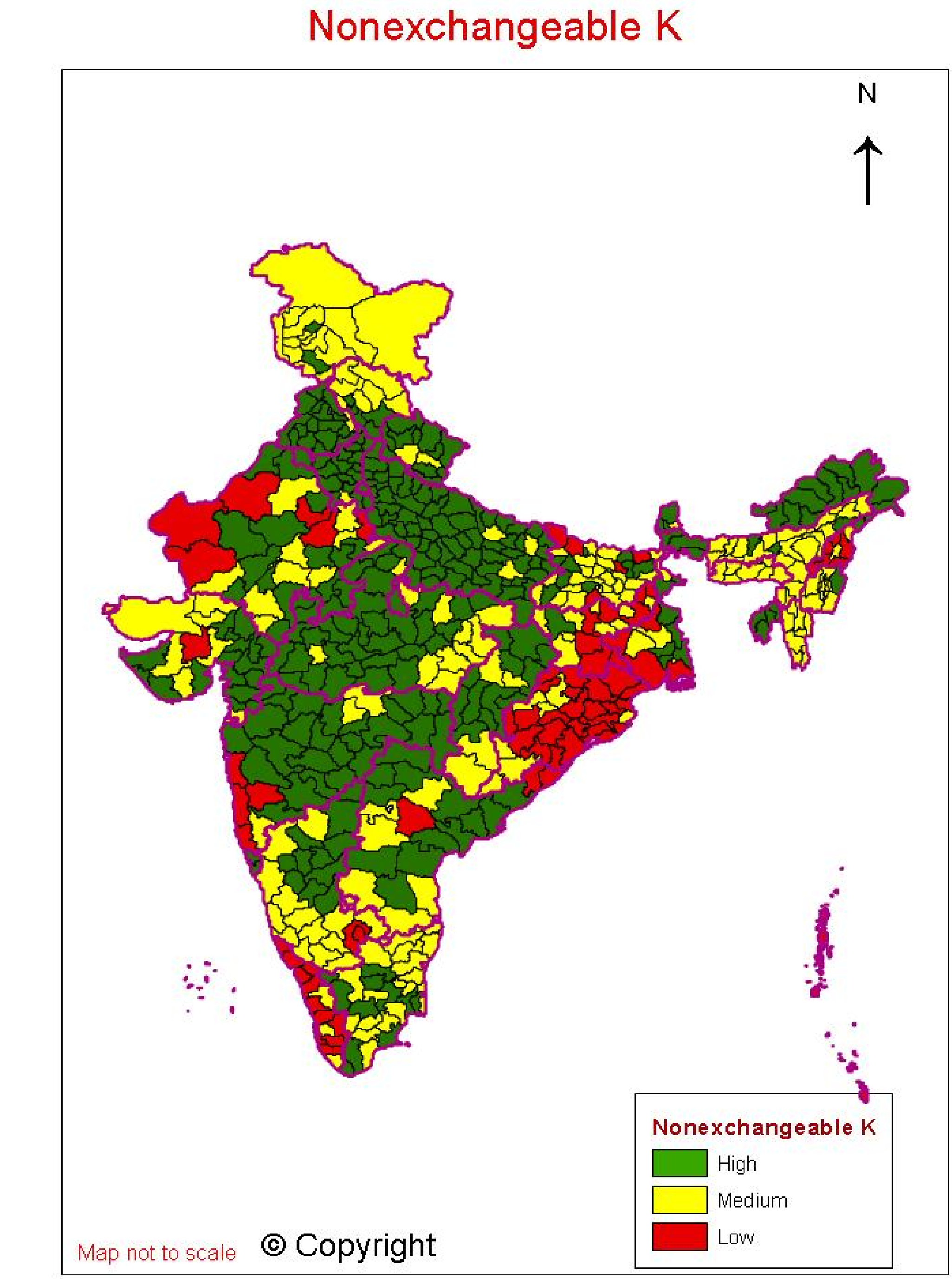
Identification of K efficient districts based on GIS maps for K fertilizer use

Based on above maps, districts were identified with low, medium and high in exchangeable as well as nonexchangeable K fractions (Map 1, 2, 3). In addition to the district level based maps which are administrative boundaries, attempts were made to obtain the status of exchangeable and non exchangeable K information on Agro Ecological Region (AER) and Agro Ecological Sub Region (AESR) wise also. The AER & AESRs are derived by NBSSLUP based on information such as climate, soils, degradation status etc, which are suggested to be used for agricultural planning purposes.

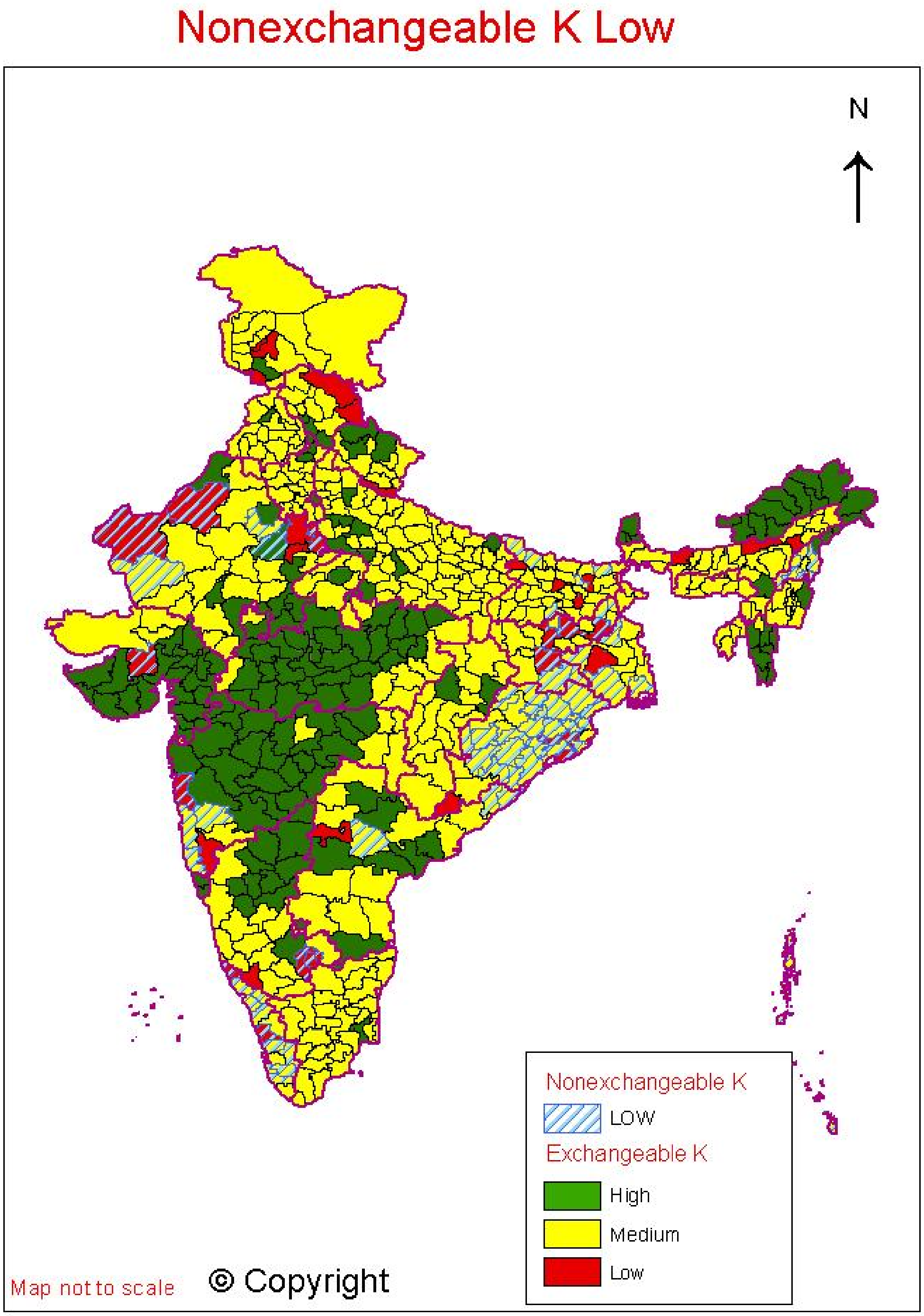
Exchangeable K



Map 1. District wise exchangeable K status of Indian soils (Map is copy right protected)



Map 2. District wise nonexchangeable K status of Indian soils (Map is copy right protected)



Map 3. Districts with low nonexchangeable K super imposed on exchangeable K map (Map is copy right protected)

Nine categories of districts were identified in combination of exchangeable and nonexchangeable K fractions (Srinivasarao and Khera, 1994a; Srinivasarao and Takkar, 1997a; Srinivasarao et al., 2007a). Fifteen districts were identified where both exchangeable and nonexchangeable K status was low (Category I) (Table 1).

Table 1. Categorization of Indian soils based on GIS based K fertility maps including exchangeable and non-exchangeable K reserves of soils

Category	Exchangeable K	Non Exchangeable K	No: of districts	Recommendations
I	Low	Low	15	K in fertilization is must
II	Low	Medium	18	K fertilization is essential
III	Low	High	2	K additions at critical stages of crops improve yield levels.
IV	Medium	Low	58	Continuous cropping needs K addition at critical stages as nonexchangeable K fraction does not contribute to plant K nutrition substantially.
V	Medium	Medium	115	Maintenance doses of K may be required for intensive cropping systems
VI	Medium	High	172	Crops may not need immediate K additions.
VII	High	Low	1	Long term cropping would need K additions after few years
VIII	High	Medium	24	K application is not required immediately.
IX	High	High	129	K application is not required.

NB: Exchangeable K: Low=<50 mg kg^{-1}, Medium= 50-120 mg kg^{-1}, High= >120 mg kg^{-1}
Nonexchangeable K:Low=<300 mg kg^{-1}, Medium= 300-600 mg kg^{-1}, High=>600 mg kg^{-1}

The districts under category I and II represent mostly red, lateritic soils, light textured and shallow soils. Since both the K fractions were low, K supply to crops grown on these soils is a must and therefore regular K fertilization should be done considering crop K removal and the recommendations generated in the local university or Indian Council of Agricultural Research (ICAR) institutes. Another 18 districts are categorized under Category II where exchangeable K was low while nonexchangeable K was medium. These soils also represent light textured and acidic alluvial soils. As exchangeable K was low and medium K non exchangeable reserves, regular K application is essential. Two districts under Category III, where exchangeable K was low and nonexchangeable K was high, K addition at critical crop stages is required to improve the crop yields. Category IV covers 58 districts where exchangeable K medium and nonexchangeable low. These districts represent light textured alluvial, red and lateritic, acid sulfate and sandy soils. These soils need considerable attention from K management point of view. Continuous cropping on these soils result in depletion of soil reserve K, therefore, K addition at critical stages is required. If K demanding cropping systems are like rice-wheat, rice-wheat-fodder, sunflower based, potato and other tuber crops, banana, intensive fodder and vegetables based systems are grown regular additions of K is essential.

Category V covers 115 districts of India, where both exchangeable and nonexchangeable K fractions were medium. These regions represents various types of soils from acid to alkaline, red, medium to deep black and alluvial. As both the fractions were medium, K additions are required for high value, quality (tobacco) and K exhaustive crops (sugarcane, potato etc.). Another 172 districts fall under Category VI, where exchangeable K was medium and nonexhangeable K was high. These districts represent variety of soils starting from heavy textured red soils, medium to deep black soils, heavy textured alluvial soils, high organic carbon Mollisols. Crops may not need immediate application of K unless specific K loving crops like banana and potato are grown. One district (Jaipur) fall under Category VII, where exchangeable K was high and nonexchangeable K was low. This district represents medium deep alluvial soils with less K bearing minerals. Long term intensive cropping would need some maintenance level of K. Category VIII cover 24 districts where exchangeable K was high and medium nonexchangeable K. These districts represent medium to deep black soils, fine textured alluvial and red soils with sufficient K rich mica. Potassium application is not required immediately. Category IX represents 129 districts where both exchangeable and nonexchangeable K was high. These soils represent deep black and fine textured alluvial soils and show higher long term K supplying power and do not require K application.

The next step in the utilization of these maps is to identify the dominant cropping systems in these low to medium exchangeable and nonexchangeable K districts and apply quantities of requisite K so that production potential can be realized in a shorter period.

Verification of the GIS K fertility map categorization with Crop responses

Above recommendations obtained from GIS based K fertility maps have been verified with existing crop response data published for these regions. In districts of Bangalore rural areas, where both exchangeable and nonexchangeable K reserves were low (category I) a significant response to K in groundnut and ragi crops were found (Naidu et al., 1996; Srinivasarao et al., 2000b). Under long term cropping at Bangalore rural, there was a decrease in exchangeable K from 123 kg ha^{-1} to 66 kg^{-1} under N P treatment and underlined the severe yield decline in ragi and maize yields in subsequent years under 100 % N and 100 % NP with drastic depletion of soil reserve K. Similarly in light textured alluvial soils where exchangeable K was low and nonexchangeable K was medium (category II) significant yield responses of various field crops were obtained due to K application (Swarup and Srinivasarao, 1999; Tandon and Sekhon, 1988). In light textured Alfisols of Rangareddy district of Andhra Pradesh, sorghum responded significantly to added K (Swarup and Srinivasarao, 1999). In soils of category III, while exchangeable K was low while nonexchangeable K was high, response of field crops to moderate amounts of K was obtained (Swarup and Srinivasarao, 1999). In category IV soils where medium exchangeable K and low nonexchangeable K, crop response to K application was significant in later years of long term cropping. Similarly in several districts of Orissa, where nonexchangeble K is low, continuous rice-rice cultivation resulted in the significant response to K. Deep black and alluvial soils under category VIII and IX where high exchangeable K and medium to high nonexchangeable K applied K to field crops was applied K was rare (Srinivasarao et al., 2011; Subbarao and Srinivasarao, 1996).

Conclusions

Using GIS system enables a more precise approach for K fertilizer recommendations in the varied soils of India, which vary widely in their K status as reflected by variations in readily available K and nonexchangeable K reserves. This GIS based K mapping exercise is the first of its kind in the country where two distinct fractions of K were involved in categorizing soils for K fertility management and identified priorities for K application. However, the maps generated with available information using GIS technique, should be interpreted with some caution. At many locations, high levels of K reserves in deeper layers indicate their substantial potential to supply K from sub-soil K to crop under intensive systems of production. As Alfisols and Oxisols and light textured Inceptisols were definitely low in soil K reserves, their K management needs to be adapted. Inceptisols with higher ratio of nonexchangeable to exchangeable K, have larger reserves but lower readily available K and so need maintenance application levels of K. Vertisols and associated soils with relatively low levels of this ratio have higher available K but low to medium nonexchangeable K which under long term cropping, may get depleted faster. Soils were categorized by including nonexchangeable K along with exchangeable K, as contribution of nonexchangeable is substantial in K removals by different production systems. Soil with low levels of both exchangeable and nonexchangeable K, K application must be done to realize full yield potential of different cropping systems. Similarly for different categories, K recommendations have been suggested based on soil K reserve status. This categorization of soils into different groups provides a comprehensive assessment of K supply for plant uptake and better recommendation of potash application. Fertilizer recommendations evolved on the basis of soil test calibration including both exchangeable and nonexchangeable K reserves and crop response studies carried out on soils classified should be extended immediately for crop K advisory purposes. This work resulted in the identification of the Indian districts where both the readily available and nonexchangeable soil K are low and where K application is essential. Where nonexchangeable K is low and medium in several districts, continuous cultivation of crops gradually results in soil K depletion and reduction in crop yields. The K fertilizer material should be made available in the regions or districts where soil K reserves are low and high K requirement crops are grown during crop season at the village level to ensure optimization of potash fertilizer application.

References

CRIDA. 2004. Annual report 2009-2010, CRIDA, Hyderabad. P. 138

Ghosh, A.B. and R. Hasan. 1976. Available potassium status of Indian soils. Ind Soc of Soil Sci. Bulletin No. 10:1-5.

Global soil data task group. 2000. Global gridded surfaces of selected soil characteristics (IGBO.DIS). Data available on-line http://www.daac.ornl.gov from oak ridge national laboratory, Distributed active archive centre, Oak Ridge, Tennesse.

IMD. 2005. High resolution (1^ox1^o), Daily gridded rainfall data for Indian region (1951-2003)

Mengel, K. and Uhlenbecker K. 1993. Determination of available interlayer potassium and its uptake by ryegrass. Soil Sci. Soc. Am. J. 57: 761-766.

Mengel, K, and Busch, R. 1982. The importance of the potassium buffer power on the critical potassium level in soils. Soil Sci. 133: 27-32.

Muhr, G.R., N.P. Datta, H. Shankara Subramoney, V.K. Leley, and R.L. Donahu. 1965. Soil Testing in India. USAID, New Delhi, pp.120.

Naidu, L.G.K., R. S. Reddy, E.V.S. Prakasa Rao, P. Krishan and R.A. Nasre. 1996. Potassium deficiency in crops-an emerging problem in red and lateritic soils. J. Potassium Res.12: 23-29.

NAIP. 2005. NAIP production system research, Completion report, Rainfed agro-eco systems directorate, CRIDA, Hyderabad.

Sehgal, J.L., D.K. Mandal, C. Mandal, and S. Vadivedu. 1992. Agro-ecological regions of India. National Bureau of Soil Survey and Land Use Planning, ICAR, Nagpur, India.

Sekhon, G.S., M.S. Brar and A. Subba Rao. 1992. Potassium in some benchmark soils of India. Potash Research Institute of India, Gurgaon, Haryana, India. p. 1-82.

Siebert, S., Doll, P., Ferick, S., Hoogeveen, J. and Franken, K. 2007. Global map of irrigation areas version 4.0.1. Johann Woffgang Goelte University, Frankfurt, Germany, Food and agriculture organization of the united nations, Rome, Italy.

Solankey, B. S., D.A. Shinde, K.S. Yadav and J. Singh. 1992. Response of wheat to K application in swell-shrink soils in relation to water-soluble K contents. J. Potassium Res. 7: 9-19.

Sparks, D.L, and Huang, P.M. 1985. Physical chemistry of soil potassium In:Potassium in Agriculture (Munson, R.D. et al., Ed) Soil Science Society of America, Madison, Wisconsin, U.S.A.pp 201-276.

Srinivasarao,Ch. and Khera,M.S. 1994a. Potassium replenishment capacity of some ustrochrepts at their minimal exchangeable K in relation to clay mineralogy. Z. Pflanzenernahr.Bodenk. J of Plant Nut and Soil Sci. 157(6): 467-470.

Srinivasarao, Ch., Subba Rao, A. and Ganeshmurthy. A.N. 1995a. Status and Desorption kinetics of potassium in some swell - shrink soils. J. Indian Soc. Soil Sci. 43 (3): 356-360.

Srinivasarao,Ch. and Khera,M.S. 1995b. Fixation of added potassium and fertiliser K requirements of illite dominant soils as affected by K depletion. J. Indian Soc. Soil Sci. 43(3):405-407.

Srinivasarao, Ch. and Takkar, P.N. 1997a. Evaluation of different extractants for measuring the soil potassium and determination of critical levels for plant available K in smectitic soils for sorghum. J. Indian Soc. Soil Sci. 45:113-119.

Srinivasarao, Ch. and M.S. Khera. 1997b. Response to potassium in K-depleted Ustochrepts in relation to K fixation. J. Potassium Res. 12: 351-357

Srinivasarao, Ch., Bhanu Prasad, B., Prasad, P.R.K., Bansal,S.K. and Subba Rao, A., and Takkar, P.N. 1997c. An Assessment of potassium reserved and K desorption in Six micaceous red soils using conventional estimates and Electro-ultrafiltration. J. Indian Soc. Soil Sci. 45:44-47..

Srinivasarao,Ch., Pal,D.K. and Takkar,P.N. 1998a. Mathematical models to study the kinetics of potassium desorption from swell-shrink soils of central India in relation to mineralogy. J of Plant Nut and Soil Sci. 16(1): 67-72.

Srinivasarao,Ch., Anand Swarup, Subba Rao,A., Venugopal,V. 1999. Kinetics of nonexchangeable K release from Tropaquept as influenced by long-term cropping, fertilization and manuring. Aus Jour of Soil Res. 37(2): 317-328.

Srinivasarao,Ch., Bansal,S.K. and Subba Rao,A. 2000a. Relationship between some forms of potassium and neutral normal ammonium acetate extractable K in major soil series of India. J. Indian Soc. Soil Sci. 48 (1): 27-32.

Srinivasarao, Ch., A. Subba Rao and S.P. Singh. 2000b. Nonexchangeable potassium release in one molar nitric acid: Evaluation of different modes of boiling the soil-acid suspension.Comm. Soil Sci. Pl. Anal. 31: 905-911.

Srinivasarao, Ch., Subba Rao,A. and Rupa,T.R. 2000c. Plant mobilization of reserve potassium from fifteen smectitic soils in relation to mineralogy and soil test potassium. Soil Sci. 165(7): 578-586.

Srinivasarao,Ch., Rupa,T.R., Subba Rao,A. and Bansal,S.K. 2001a. Sub-soil potassium availability in major benchmark soils series of India. Commun. Soil Sci. Plant Anal. 32 (5&6): 863-876.

Srinivasarao, Ch., Datta, S.C. and Khera, M.S. 2004. Degradation illite clay as a consequence of potassium depletion under intensive cropping. Ind Jour of Ferti. 49 (5): 51-56.

Srinivasarao,Ch., Rupa,T.R., Subba Rao., Singh,S.P. and Bansal,S.K. 2006a. Kinetics of nonexchangeable potassium release from important benchmark soils of India: Effects of mineralogy, soil depth and extraction media. Commun. Soil Sci. Plant Anal. 36 (3&4):1-19

Srinivasarao, Ch, Rupa T.R, Subba Rao A, Ramesh G, Bansal S.K. 2006b. Release kinetics of nonexchangeable potassium by different extractants from soils of varying mineralogy and depth. Commun. Soil Sci. Plant Anal. 37: 473-491.

Srinivasarao, Ch., Vittal, KPR., Tiwari, KN., Gajbhiye, P.N. Sumanta Kundu, Pharande,A.L., Yellamanda Reddy, Y. and Shankar, M.A. 2007a. Potassium supplying characteristics of twenty one soil profiles under diverse rainfed production systems. J. Indian Soc. Soil Sci. 55:14-22.

Srinivasarao, Ch., Vittal, KPR., Tiwari, KN., Gajbhiye, PN. and Kundu, S. 2007b. Categorization of soils based on potassium reserves and production systems: implications in K management. Aus Jour of Soil Res. 45: 438-447.

Srinivasarao, Ch., Subba Rao, A., Rao, K.V., Venkateshwarlu, B., and Singh, A.K. 2010. Categorization of Districts based on Non-exchangeable Potassium: Implications in efficient K fertility management in Indian agriculture. Ind Jour of Ferti. 6 (7): 40-56.

Subba Rao, A, Srinivasarao Ch. 1996. Potassium status and crop response to potassium on the soils of Agro-ecological regions of India. IPI Research Topics No.20. International Potash Institute, Basel, Switzerland. p 57.

Subba Rao, A., M.V.R. Sesha Sai and S.K. Pal. 1993. Non-exchanageable potassium reserves and their categorization in some soils of India. J. Indian Soc. Soil Sci. 41: 667-673.

Swarup, A. and Srinivasa Rao,Ch. 1999. Current status of crop responses to nutrients. Experiences from All India Coordinated Research Project on Long-Term Fertilizer Experiments. Ferti News. 44 (4): 27-43.

Tandon, HLS, and Sekhon GS. 1988. Potassium research and agricultural production in India. Fertilizer Development and Consultation Organization, New Delhi, India.