Site-specific Crop Nutrient Management for Precision Agriculture – A Review

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Authors' contributions

This work was carried out in collaboration among all authors. Author TG designed the study and wrote the initial draft of the manuscript. Author PKY managed the literature searches. Author GLC revised the initial draft. Author AK helped in preparation of manuscript as per journal format. All authors read and approved the final manuscript.

Review Article

ABSTRACT

Present irrational crop and nutrient management practices have raised several concerns of high merit. The concerns include low factor productivity or nutrient use efficiency (NUE), declining crop productivity, farmer's profitability, impaired soil health and ecological contamination. Site-specific nutrient management (SSNM), after considering indigenous nutrient supplying capacity of soil using plant and soil analysis, can feed the crop in synchrony with its nutrient requirement in different physiological growth stages. Besides, several modern geospatial techniques viz. remote sensing techniques, geographic information system (GIS), global positioning system (GPS), proximal sensing; information and communication technologies (ICTs) including decision support system, smartphone apps and web services can also assist in diagnosis of soil and crop nutrient status, fertilizer recommendation and its dissemination to users. Optical and thermal remote sensing can effectively detect crop stress including nitrogen (N) deficiency through several vegetation indices especially normalized difference vegetation index (NDVI). GIS techniques with spatial data acquired by GPS, can create spatial variability map and management zone (MZ) for precise farm operations including variable rate fertilization. Proximal crop sensors viz. chlorophyll meter and Green Seeker can also recognize crop nitrogen status and promote fertilizer N use efficiency by synchronizing fertilizer N supply with crop requirement. Even proximal soil sensing using electromagnetic radiation

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and contact electrode can estimate soil properties like soil pH, electrical conductivity, major and micronutrient content. Several decision support systems such as QUEFTS based model, crop manager, nutrient expert® and smartphone apps like 'crop doctor' can suggest for precise application of agro-inputs to rural youths and farmers. Yield monitoring and mapping tool can generate historical GIS database for spatial variability of crop yield under farmers' crop management practices and assessment of nutrient uptake. Variable rate machinery based on variability map and sensor technologies can also be used for fertilization under different management zones. Therefore, SSNM technologies can enhance NUE; improve and sustain crop productivity, profitability; avoid nutrient wastage; maintain good soil health and environmental safety.

1. INTRODUCTION

In context of doubling farmers' income and building self-reliant India, site-specific crop nutrient management is one of promising techniques to improve soil and environmental health [1], sustain higher agricultural productivity and national food security. Site-specific nutrient management (SSNM), through its potentiality for eco-friendly sustainable agricultural production, can be one of the means to alleviate all forms of hunger and malnutrition by 2030 under sustainability development goal. Essential plant nutrient inputs contribute to 30-50% of crop yield worldwide [2] but the recovery efficiency of fertilizer nutrients is substantially low with range of about 20-40%, 15-20% and 40-50% for N, P and K, respectively and 5-12% for secondary and micronutrients [3]. Important reasons of low nutrient use efficiency are poor soil health, widespread multi-nutrient deficiencies, imbalanced nutrient use (NPK consumption ratio - 6.6:2.6:1 for financial year (FY) 2018-19 in India as per latest statistical database of Fertilizer Association of India (FAI). Conventional nutrient management recommendations had been developed by central and state organization for almost all cultivated crops in India. But there are limitations of blanket (fixed-rate, fixed-time) fertilizer recommendations due to non-accountability of the variability in the inherent soil fertility and other edaphic factors [4]. However, recognizing the demerit of existing blanket fertilizer recommendations, the concept of SSNM was developed to synergize crop-soil nutrient dynamics considering farm nutrient variability and it had been proven to be superior to farmers' field practices in term of nutrient use efficiency and economic yield for several crops such as rice [5], wheat [6], maize [7] etc.

Recent development in information technology (IT) sector including computer & electronics, communication and space technology impacted positively in development and dissemination of agricultural technologies. In precision agriculture, SSNM technologies are means for crop fertilization. Laboratory testing and field based practices; map and proximal sensing based fertilizer recommendation; yield monitoring and mapping; variable-rate application (VRA) equipments are a few approaches for SSNM practices. Right farm management information system (FMIS) was developed and utilized for variable rate application (VRA) of farm agri-inputs as per in-built decision support systems (DSS) and prediction models of diverse data sources [8]. Geospatial database, an input data of the FMIS, can be acquired by remote sensing images including unmanned aerial vehicle (UAV) images of canopy, soil, topography, and climatic data as well as proximal sensing method. Farm gross profit was enhanced and agricultural waste was reduced with promotion of farmer's livelihood and environmental safety [9]. VRA technology with inbuilt GPS system will promote to harvest the fruits of frontier technologies by Indian farmers in future. This paper has been attempted to describe recent SSNM technologies and tools applied in precision agriculture for enhancing nutrient use efficiency (NUE), crop productivity, profitability and environmental safety.

2. SITE-SPECIFIC CROP NUTRIENT MANAGEMENT AND ITS APPROACHES

Site-specific nutrient management (SSNM) is the dynamic, crop season specific, field specific nutrients management to synchronize the supply and demand of nutrients in accordance with their disparities in cycling through soil plant systems [10]. The SSNM approach is being attempted to use 4R Nutrient Stewardship – right source, dose, time and place of nutrient use. 4R Nutrient

Stewardship framework promotes to high and sustainable crop productivity, nutrient use efficiency, farmer profitability and environmental safety. Existing farm resources viz. crop residues and farm organic manures are also optimally utilized. It also takes concern of secondary and micronutrient fertilization. The benefits of SSNM approach can be amplified through integration with other best management practices (BMP) such as quality seeds, optimum plant density, good water management, integrated pest and disease management.

The basic principles of SSNM approach entail components like indigenous nutrient supply (INS) from the soil and crop nutrient requirement for attaining targeted yield. The nutrient gap *i.e.* the difference between the crop nutrient requirement and INS is managed through application of manures and fertilizers as and when required by the crop during its growth. The SSNM recommendations could be evolved in accordance with solely plant analysis or soil cum plant analysis. Recently, other modern approaches are also being followed for SSNM recommendation.

2.1 Plant Analysis-based SSNM

The approach is based on plant analysis because crop nutrient status is considered as the best indicator of crop nutrient requirement and nutrient supplying capacity of soils. The five key steps of SSNM were initially proposed by Witt and Doberman [5] for developing field-specific fertilizer NPK recommendations in irrigated lowland rice, and subsequently were effectively applied in other crops such as wheat, maize, sugarcane, onion etc. for fertilizer recommendation [11]. These are: (i) selection of yield goal, (ii) estimation of crop nutrient requirements, (iii) estimation of indigenous nutrient supplies (INS), (iv) calculation of fertilizer rates, (v) dynamic adjustment of fertilizer N applications. The yield goal or target yield is generally considered as 70-80% of potential yield (Y_{max}) or climatic-yield potential (CYP) of the specific crop variety and it can be estimated from crop growth model. The crop nutrient requirements are estimated using quantitative evaluation of fertility of tropical soils (QUEFTS) models. Indigenous nutrient supply (INS) is the total amount of a particular soil nutrient that is available to the crop during the cropping cycle under condition of other non-limiting nutrients and INS is estimated through nutrient omission plot technique in farmers' field. Field-specific fertilizer nutrient rates are computed from nutrient gap (difference between amount of crop nutrient requirement and INS) with consideration of fertilizer recovery efficiency. The computed rates of phosphorus and potassium fertilizer are generally applied as basal doses, but fertilizer nitrogen rate is dynamically adjusted and applied as per crop's need at different critical stages of crop growth. Site-specific and in-season nitrogen management can minimize the nitrogen gap in crop production and is also core for agricultural intensification and sustainability [12]. SSNM technique had shown the potentiality for increasing crop yields and promoting nutrient use efficiency (NUE) in rice [13], wheat [14], maize [15,16] etc.

2.2 Soil-cum-plant Analysis-based SSNM

Fertilizer recommendation based on analysis of soil and plant samples in a specific field or plot is literally site-specific nutrient management and it is routinely practiced in global agriculture [17-22]. Fertilizer recommendation using "targeted yield approach", actually known as site-specific nutrient management, is being advocated in India since late 1960s [23,24]. It prescribes the optimum fertilizer dose for targeted yield of crop through fertilizer adjustment equation or soil test crop response (STCR) equations based on soil and plant analysis data. For developing target yield equation or STCR based fertilizer adjustment equations of specified crop or cropping sequence in a specific region, different parameter viz. available soil nutrient content, crop nutrient requirements for a higher target yield (*i.e.,* more than 80% of variety specific potential yield - Ymax), total nutrient uptake by crop in control plots, organic plots and fertilized plots under field experiment, nutrient recovery efficiency (NRE) are estimated and subsequently, contribution of particular nutrient from soil (CS), fertilizer (CF) and organics (CO) towards crop nutrient uptake can be computed [25]. STCR equations under integrated plant nutrition system (STCR-IPNS) was developed for fertilizer prescription based on soil test and yield target for agro-horticultural crops and major cropping sequences in six agro-climatic zones of Tamil Nadu, India [26]. Site-specific fertilizer doses using STCR equations were established to fulfil nutrient requirement of the specified crop variety with targeted yield without reducing soil nutrient reserves [27].

2.3 Modern Approaches of SSNM

Map-based and sensor-based methodologies are two essential SSNM techniques for the variable-

rate application (VRA) of manures and fertilizers. Site information, existing available technology and efficient management are broad and fundamental elements of site-specific management technology. The map based SSNM techniques has three basic steps like assessment of soil and crop variability, managing the variability and its evaluation [28]. Site-specific fertilization was recommended based on nutrient variability map [29,30] and site-specific management zone [31]. The sensing system measures the desired soil properties or crop characteristics; subsequently measured data are used for fertilizer calculation utilizing certain algorithm, and finally these are used to regulate the variable rate applicator [32,33]. Nitrogen fertilizer management using proximal sensors was extensively studied and also practiced in cereals [34,35], vegetables [36] etc. Remote sensing methods using spectral and thermal approaches have potentiality to schedule nitrogen fertilization after rapid identification of nitrogen status in crop canopy across large areas [37]. Site specific management zone was developed from Green Normalized Difference Vegetation Index (GNDVI) and Soil Brightness (SOB) estimated from remotely sensed image along with soil organic carbon and nitrogen dataset [38]. Besides, DSS provides quick and smart farm management decision to users; smartphone apps and web services hasten the dissemination of SSNM technologies to the farming communities.

3. TOOLS AND TECHNIQUES OF SSNM

3.1 Soil, Plant and Water Testing

General or conventional fertilizer recommendations are provided by State Governments or State Agricultural Universities (SAUs) or central Institutes based on agro-climatic zone and agro-ecological zone in India. Fertilizer recommendations based on soil and plant test is preferable over agro-climatic zone based conventional fertilizer recommendation for achieving precision in farming, maximizing crop production, maintaining soil health, and minimizing fertilizer misapplication [39]. All India Co-ordinated Project (AICRP) on Soil Testing Crop Response (STCR) programme, initiated since 1967, has developed several fertilizer adjustment equations or STCR equations for computation of fertilizer dose considering soil nutrient availability and quantity of nutrients requirement in major crops following target yield concept. Detailed information of STCR

technology including its economic benefit and publications is available in AICRP-STCR website [40]. STCR based fertilizer recommendations offer higher economic benefits in comparison with conventionally prescribed NPK fertilizer schedules or soil fertility chart based fertilizer prescription for individual crops or cropping sequence under different soils and climatic conditions [41-44].

Soil and plant testing kits are available for in-situ analysis and fertilizer recommendation in India. Pusa Soil Test Fertilizer Recommendation (STFR) meter kit is a digital and portable soil testing mini lab, developed by Indian Council of Agricultural Research-Indian Agricultural Research Institute (ICAR-IARI), New Delhi. It can analyze fourteen soil parameters *i.e.*, soil pH, soil electrical conductivity (EC), lime requirement for acid soil, gypsum requirement for alkali soil, organic carbon, available major nutrient status viz. nitrogen, phosphorus, potassium, sulphur and micronutrients availability such as zinc, copper, iron, manganese and boron. It also gives crop- specific fertilizer recommendation for about 100 crops including field crops and horticultural crops.

3.2 Geospatial Techniques

Geospatial technologies such as remote sensing, global positioning system (GPS) and geographic information system (GIS) have enormous potentiality for spatio-temporal analysis and monitoring in agriculture [28,45]. Retrieval of soil properties viz. soil organic carbon (SOC), salinity, moisture, pH, nutrient status etc. using spectral reflectance along with spectral indices from satellite data and its spatial variability using different spatial interpolation method are used for site-specific input management for agricultural sustainability [46].

3.2.1 Global Positioning System (GPS)

Several Global Navigation Satellite System (GNSS) launched by countries within parenthesis such as NAVSTAR (United States), GLONASS (Union of Soviet Socialist Republics), Galileo (European Union), BeiDou-COMPASS system (China) etc are working globally to provide accurate position, navigation and time (PNT). Indian Regional Navigation Satellite System (IRNSS) or Navigation with Indian constellation (NavIC) has been designed to give exact real time PNT to users in India as well as surrounding region with 24×7 service availability under all

weather conditions. Several technologies such as differential GNSS, precise point positioning (PPP) method, multi-GNSS PPP, real time kinematic (RTK) – GNSS etc has significantly improved positional accuracy and also being used for precision agriculture in developed countries [47]. GPS receivers, either handheld or mounted on implements, allow users for geo-referenced sampling, data capture and farming operation in precision farming. Many operations such as the precise seeding, fertilizing, irrigating, controlling pest of crops etc are being executed observing within field plots spatial variability. GNSS can be effectively used for site-specific data analysis and applications, farm machinery guidance systems, variable rate applications and tracking/delineation in agriculture [48]. Some progressive Indian farmers had also initiated to use smartphone GPS for recording observations and applied crop management practices after receiving expert's recommendation.

3.2.2 Remote sensing techniques

These techniques are being utilized to acquire the field information from distance with sensors mounted on hand held devices, unmanned aerial vehicle (UAV) or air craft or satellite. It can be effectively used in recognizing crop species and monitoring crop growth status, soil moisture, crop nutrients, crop pest and disease infestation, yield estimation etc. Multispectral & hyperspectral remote sensing and thermal aerial imagery can be effectively used to detect crop nitrogen deficiency using normalized difference vegetation index (NDVI) and other indices. Nitrogen is constituent of chlorophyll pigments of green leaves. Nitrogen content significantly controls leaf chlorophyll content and hence it has effect on variability on purity and darkness of green colour in leaves. The formula of NDVI is presented below in equation (1).

$$NDVI = (NIR – Red) / (NIR + Red) \qquad (1)$$

Near-Infrared (NIR) and Red in equation (1) represent the reflectance in NIR and red band respectively. There is strong absorption or very less reflectance by chlorophyll pigments in blue and red regions of incident radiation, and the structure of mesophyll tissues shows high reflectance of the incident NIR radiation. Hence, there exists good correlation between crop nitrogen content and NDVI value [49].

Estimation of crop N content [50] and N-fertilization using VRT [51] was also reported with the enhanced spatial, spectral and temporal resolution of Sentinel-2 A + B twin platform and its open-accessible imagery data. Assessment of soil properties including soil fertility parameter using hyperspectral remote sensing (HRS) data from Hyperion satellite and spectroradiometer instrument was initiated and also reviewed in Indian context [52]. Soil peanut productivity zones at the eastern Nile Delta, Egypt were developed with good accuracy using soil properties, topography - slope, climate based on the structure of FAO land suitability & Spatial Multi Criteria Evaluation tree (SMCE) in GIS and subsequently field management zones were prepared with herbs infection map and soil adjusted vegetation Index (SAVI) from Landsat image data [53].

3.2.3 GIS based nutrient management

Computer GIS software, mobile GIS apps and geo-web services had been developed for geospatial analysis. GIS software is also database system and decision support system which use soil and plant nutrients attributes and location data for precision nutrient management. Multiple layers of information viz. remotely sensed data, crop yield, soil survey maps, thematic nutrient variability map etc can be stored, analysed, retrieved at will and displayed in both dataset form and map. Spatial variability mapping of soil nutrients utilizing geostatistical techniques and management zone (MZ) based STCR are recently developed approaches for precision nutrient management [54]. Development in information & communication technologies (ICTs), remote sensing technologies, data fusion viz. k-means clustering algorithm [55] and geostatistical interpolation techniques (kriging) have delineated with good precision and reliability into management zone (MZ), making it an essentially practical procedure in commercial precision agriculture. MZ delineation techniques can be utilized for variable-rate nutrient application and it improves farm productivity and efficiency contrasted with conventional uniform-rate application techniques, providing agronomical, financial and environmental benefits [56]. Google Earth is a virtual globe, map and GIS software and it uses aerial photography, satellite imagery and GIS 3D globe for mapping the entire Earth. It is a strong tool for precision agriculture through its provision of geo-referenced base layer, utility for farm planning, field delineation, geo-referenced soil

sampling, field scouting, crop health diagnosis and monitoring, VRA and yield mapping [57].

3.3 Proximal Plant and Soil Sensing

Proximal sensing technology can be utilized for plant and soil sensing for diagnosis of crop nutrient status and subsequently nutrient recommendations. Crop leaf colour at definite physiological growth stage is compared with leaf colour chart (LCC) by visual colour comparison with our natural sensor – eye for diagnosis of crop nitrogen deficiency. Leaf colour chart (LCC) and chlorophyll meter are decision tools for real time fertilizer recommendation through in-situ and periodic crop N monitoring [58]. Besides, proximal sensors viz. canopy reflectance sensor and soil sensor are also being used for estimation of nutrient status.

3.3.1 Leaf Colour Chart (LCC)

It is cheap, basic and a simple-to-utilize alternative option to diagnose the relative leaf greenness of rice, maize, wheat crops etc as an indicator of crop N status in contrast with fast and moderately costly chlorophyll meter [59]. The LCCs utilized in Asia are regularly a tough plastic strip around 7 cm wide and 13 to 20 cm long, consisting of four to six panels with colour ranging from yellowish green to dark green. Farmers monitor the leaf colour of field crops at 7 to 10 days stretches and apply N fertilizer under situation of leaves becoming more yellowish green than the critical LCC panel of the particular crop and variety.

3.3.2 Chlorophyll meter

Soil and Plant Analysis Department (SPAD) chlorophyll meter uses spectral transmittance principles for analysis of leaf N status as nitrogen is integral constituent of chlorophyll pigment in leaf and subsequent nitrogen management in synchronizing N supply and crop demand at different crop physiological growth stage. The instrument consists two light emitting diodes (LEDs), which discharge two different radiations at wavelength of 660 nm (red) and 990 nm (infrared) sequentially without any sample during calibration and by clamping the unplucked leaf tissues in measuring heads. Generally, Leaf chlorophyll has peak absorbance in red band but almost no absorbance in IR band. The remainder transmitted radiation from leaf is converted into analog electrical signal within silicon photodiode detector, subsequently boosted by amplifier and converted into digital signal by A/D converter. Subsequently, microprocessor reads the digital signals. The ratios of the intensity in IR and Red band in both without any sample and with sample is calculated and used in microprocessor to calculate the SPAD value, which corresponds to the chlorophyll content in the sample leaf.

Fertilizer Nitrogen recommendation based on critical SPAD reading depends on specific crop species, crop variety, crop growth stage, leaf characteristics, soil type and nutrient status, environmental factors etc. SPAD/LCC-based N management schedules in several crops has been established to be advantageous from on-station and on-farmers' field trials in India and elsewhere with respect to nitrogen use efficiency, yield grain and economic profits over the traditional N recommendation. SPAD threshold or critical value for rice had been properly described [60]. The critical SPAD value was 37.5 for rice and topdressing of 30 kg N ha^{-1} at maximum tillering stage of wheat under the SPAD value less than 44 increased the crop productivity in rice-wheat cropping system at Punjab, India [61]. Nitrogen application @ 30 kg ha^{-1} at planting, @ 45 kg ha^{-1} at crown root initiation (CRI) stage and @ 30 or 45 kg ha^{-1} at maximum tillering (MT) stage in condition of SPAD value to be ≥ or < 42.5, respectively for irrigated wheat crop produced grain yields at par with conventional N recommendation (60 kg N ha^{-1} at planting + 60 kg N ha^{-1} at CRI stage) but with higher fertilizer nitrogen use efficiency in north-western India [62]. SPAD-based (≤37) N application enhanced agronomic nitrogen use efficiency in winter season maize crop in contrast with STCR equation-based N application [63].

3.3.3 Canopy reflectance sensor

Crop canopy reflectance sensors viz. GreenSeeker, Crop Circle and RapidSCAN measure spectral reflectance of visible and near-infrared (NIR) band from crop canopies to be interpreted for crop nitrogen (N) stress. GreenSeeker sensor use red spectra (650 nm) and NIR spectra (770 nm). The active optical sensors are mainly based on concept of normalized difference vegetation index (NDVI). It is good indicator for crop vigor, yield, crop biomass, chlorophyll content, crop nitrogen content, crop water stress, pest infestation etc. Active sensors can estimate the crop N content and subsequently for management of N-fertilizer in currently-grown cereal crops on the NDVI concept [64]. The sensors translate the readings

into N-fertilizer rate using certain algorithm in calibration with local reference strips getting adequate N-fertilizer.

Crop Circle sensor uses green spectra (590 nm) and NIR (880 nm) spectra and RapidSCAN sensor uses 670 nm, 730 nm and 780 nm spectra. Crop Circle sensors can also be effectively used at advanced crop growth stages while crop leaf area index (LAI) crosses over 2.0 value and potential crop yield than the red NDVI determined by GreenSeeker sensor [65]. Handheld, pole mounted and tractor mounted model of canopy optical sensor are being commercially and internationally marketed by NTech Industries, Holland Scientific, Trimble etc.

Nitrogen fertilization optimization algorithm was developed [32] for optical sensors in rice and wheat crops for Indo-Gangetic plains, India and suggested GreenSeeker as a significant device for rational N management in the rice-wheat system. In another study, nitrogen application @ 140 kg ha^{-1} in four split doses *i.e.* @ 30 kg ha^{-1} as basal, 60 kg ha^{-1} at CRI stage and Greenseeker guided nitrogen application @ 40 kg ha^{-1} at 45 days after sowing (DAS) during second irrigation and 10 kg ha^{-1} at 65 DAS (third irrigation) showed highest benefit cost ratio in wheat production at Kanke, Ranchi, India [66]. Hand-held chlorophyll meters (SPAD meter and atLeaf) and canopy reflectance sensors (GreenSeeker and Crop Circle) can be effectively utilized by small land holding farmers for fertilizer nitrogen management in cereals (rice, wheat and maize) in developing countries [34]. They observed that sensor based nitrogen management had reduced the dose of fertilizer nitrogen application, increased crop productivity and enhanced nitrogen use efficiency.

3.3.4 Proximal soil sensing

Proximal soil sensing (PSS) is characterized as the utilization of field-based sensors to acquire signals from the soil when the sensor's detector is in contact with or close (within 2 m) the soil. Proximal soil sensors are categorized as invasive or non-invasive; stationary or mobile; in-situ or ex-situ; direct or indirect and active or passive type [67]. Different band of electromagnetic radiation (EMR) such as neutron radiation, γ-ray, X-ray, ultra violet (UV), visible, NIR, mid-IR, microwave, radio-waves and also laser beam can be used for assessing soil properties in proximal sensing technology. Infra-red spectroscopy can also be used for estimation of

soil carbon and its fractions, major nutrients such as potassium, calcium and magnesium [68-70]. Laser induced breakdown spectroscopy (LIBS) was effectively and directly utilized to assess total carbon, total nitrogen, total potassium, other major nutrients, micronutrient elements and heavy metals [71-74].

Contact sensors including electrochemical sensors, ion selective electrodes (ISEs) and ion-sensitive field effect transistors (ISFETs) can be effectively used for measurement of soil pH, lime requirements [75-77], salinity, sodicity and nutrient sensing such as nitrate, available phosphorus, potassium, calcium, sodium, micronutrients [78-82]. Proximal soil sensing was also been systematically reviewed [83]. Soil sensors and internet of things (IoT) soil monitoring systems were developed for assessment of soil pH, electrical conductivity, moisture content, temperature and soil nutrients viz. nitrogen, phosphorus and potassium by multinational companies (MNCs) like Jingxun Changtong Electronic Technology Co. Ltd. Weihai, China [84]; Racketail, Gurugram, India [85] etc.

3.4 Information and Communication Technologies (ICTs)

ICTs such as decision support system, smartphone apps and web services are continuously utilized by policy makers, extension workers, farmers etc for adoption of agro-technologies including crop fertilizer recommendation at present development era of information technology.

3.4.1 Decision Support System (DSS)

Several researchers attempted to use DSS, which are interactive computer based frameworks or software system that use information and models, for crop yield estimation and fertilizer recommendation in agricultural system. Agricultural Production Systems Simulator (APSIM) is a comprehensive model used for predictions of crop production and also simulation of biophysical processes within agricultural systems and user can specify the application of solid fertilizer to the APSIM fertiliser module [86]. The Decision Support System for Agro-technology Transfer (DSSAT) software simulates crop growth, development and yield as a function of the soil-plant-atmosphere dynamics and are tools to enable effective utilization of the crop simulation models

[87]. InfoSoil model, DSS for soil quality assessment and fertilizer recommendation was developed by Unit of Simulation and Informatics, ICAR-IARI, New Delhi. There was also component of fertilizer recommendation in the Decision Support System (DSS) on Pulses in India [88]. Design of variable-rate nitrogen application along with field delineation can be done based on the vegetation index (VI) generated from Sentinel-2 satellite data all across the globe in CropSAT, an interactive decision support system [89]. Other commonly used DSS was described below.

QUEFTS based fertilizer recommendation: QUEFTS model can be utilized for quantitative assessment of the native fertility of tropical soils, utilizing determined yields of unfertilized maize as a measuring stick [90]. QUEFTS model is also an aid in quantitative land assessment through its capability to predict the soil nutrient supplying capacity to crop. The QUEFTS model principally estimate crop yield potential at an agro-ecological region accounting the NPK nutrient interactions. The first version was used for maize crop and subsequently the generic version of QUEFTS *i.e.,* CROPFERT had been used for all type of crops for estimation of crop nutrient requirements. QUEFTS model was validated for wheat at Nadia district, West Bengal, India [91], sweet potato (*Ipomoea batatas* L. Lam) in major growing Indian regions [92] and other several crops for site-specific and balanced fertilization.

Nutrient expert: Nutrient Expert® (NE), as developed by International Plant Nutrition Institute (IPNI), is a computer or mobile based DSS or tool for site-specific fertiliser recommendations for cereal crops such as rice, wheat, maize etc. It also predicts the attainable crop yield and fertilizer yield response from site information and underlying algorithm for fertilizer recommendation was generated from on-farm trials (OFTs) using SSNM principle. It also uses the features of the growing environment, farmer's cropping sequence, soil fertility indicators, crop residue management & fertiliser inputs and current crop yields at farmers' field [93]. The software, also updated over the periods, is freely downloadable from the IPNI website for nutrient recommendation in cereals viz. rice, wheat and maize production as applicable to several IPNI regions viz. China, South Asia including India, Southeast Asia, Sub-Saharan Africa and North Africa [94].

Crop Manager: Crop Manager®, as developed International Rice Research institute (IRRI), is mobile and computer based decision making tools that provide site and season specific fertilizer recommendation based on SSNM principles and crop management guidelines in rice, wheat and maize crops. Rice Crop Manager for Bangladesh and Philippines; Rice Agro-advisory service for Indonesia; Crop Manager for Rice-based Systems (CMRS) Bihar Beta version, Rice-Wheat Crop Manager for Eastern Uttar Pradesh (UP) and Rice Crop Manager for Odisha in India were released and are now available at IRRI website with aims of sustainable productivity for rice-based cropping systems and increase farmer's net profit [95]. CMRS provided customized crop and nutrient management directives as per an individual farmer's need under irrigated and rainfed condition of Bihar [96]. Extension workers, crop advisors, agro-input dealers and service providers can easily recommend fertilizer application based on information provided by farmers on crops and soil.

3.4.2 Smartphone apps and web services

National informatics Centre (NIC), Ministry of Elecronics and Information Technology (MeitY) launched 'Umang' mobile app and being upgraded continuously for providing digital governmental services to each Indian citizen. This is all-in-one single, unified, secure, multichannel, multilingual, multiservice mobile application. There is also provision of soil fertility status and fertilizer information. Another app 'Crop Doctor' developed and launched by Indira Gandhi Krishi Vishwavidyalaya – National Informatics Centre (IGKV-NIC), India can be used for nutrient deficiency diagnosis and recommendation in several crops. 'Fertilizer calculator' app, developed by ICAR-Central Coastal Agricultural Research Institute (ICAR-CCARI), Goa, is available in playstore for android smartphone and it can be used for calculating fertilizer quantity as per available stock in any locality after availing the soil fertility information and recommended fertilizer dose from experts. Ag PhD (South Dakota, United States) developed 'Ag PhD Crop Nutrient Deficiencies' [97] to identify nutrient deficiencies to aid decision making in fertilization tasks for a wide variety of crops. Other several android apps were developed by multinational companies for providing crop-specific fertilizer recommendation.

Department of Agriculture, Co-operation and Farmers Welfare, Govt. of India launched soil heath card scheme nationally on 19th February, 2015 and developed both website [98] and 'Soil Heath Card' mobile app. Based on detailed information of farmers, land, crop and available fertilizer, soil health card with fertilizer recommendation can be provided to each farmer after testing soil samples in Soil Testing Laboratory. Under this scheme, ICAR-National Burreau of Soil Survey and Land Use Planning (ICAR-NBSS & LUP), Nagpur also customized 'Soil Health Card' app. This is a geographical information system (GIS)-based application which uses GeoServer map. The app uses the potentiality of GeoServer to connect existing spatial information to web-based maps such as Google Maps. It has potential to provide soil fertility status alongwith manures and fertilizer recommendation against each land plot at cadastral level map.

3.5 Yield Monitoring System

Yield monitoring and mapping are key elements of precision farming. Yield monitors can estimate location specific crop yield and dynamically generate spatial variability map of crop yield. Generally, the system, installed on modern harvesting equipment, has a GPS receiver, a mass flow sensor or a group of sensors and a data acquisition system. Yield monitor data can be useful for several management purposes such as estimating crop nutrient uptake, productivity, profitability, developing management zones, analyzing impacts of crop management skills and effect of environmental factors on crop production [99]. Long term yield monitoring makes a remarkable GIS dataset that helps farmers to effectively recognize spatial yield variability within a field for better decisions of variable-rate application. Research and commercialization of this technology had been done for several crops such as grain crops [100], maize [101], groundnut [102], Sugarcane [103], cotton, potato, onion, sugar beet, tomato etc [104].

3.6 Variable Rate Technology (VRT)

Proper assessment of within-field spatial variability, effective input-crop response models and cost effective technological innovation are pre-requisite for variable rate fertilization [105]. VRT is used to adjust the agricultural inputs at right dose in accordance with site-specific requirement of cropping systems at the right

place and time. Variable-rate machineries uses a) precise positioning in the field with differential global positioning system (DGPS) b) correct spatial variability information through pre-derived map or soil and crop sensing technology and c) variable rate controllers for automatic precise fertilizer application based on pre-derived input application maps or on-the-go sensing and calibrated fertilization. Map-driven and on-the-go sensor tractor-based VRT systems including unmanned aerial vehicles like drone are being effectively utilized for precise fertilizer-application in large fields [56,106,107]. The crop sensing system can be operated at day or night and in foggy or cloudy weather based on principles of active and passive sensing, can be mounted on booms in most sprayers/spreaders and works with most variable rate controllers and delivery systems. It utilizes optical sensors for quantitative measurement of the crop variability and prepares a targeted prescription to manage the crop variability. This variable rate fertilization was used for improved soil fertility management, agronomic efficiency and crop productivity [108] but major constraints for VRT machineries are highly expensive at farm level, which should be tackled through adequate policy instruments [109].

4. CONCLUSION

Irrational crop management and injudicious fertilizer use has led to a declined in NUE, crop yields and marginal farmers' profitability. A new paradigm of farming practices including site-specific crop fertilization using 4R-nutrient stewardship has tremendous potentiality in enhancing food production. The SSNM technologies are feeding crops with nutrients as and when required after identifying the spatial variability of inherent soil nutrient supplying capacity. Modern soil and plant testing; geospatial techniques including remote sensing, GIS and GPS; proximal canopy and soil sensing; ICTs such as decision support systems, smartphones apps, web services etc are frontier tools for SSNM in precision agriculture. Proximal crop sensing such as canopy reflectance and transmittance sensors; proximal soil sensing using electromagnetic radiation (EMR) and contact sensors viz. electrochemical sensors, ion selective electrodes (ISEs) and ion-sensitive field effect transistors (ISFETs) are sensing the nutrient status and recommending manures and fertilizer application towards crop production. ICTs viz. nutrient decision support tools, web based services, smartphones apps etc. facilitate

the dissemination of effective agro-technologies including fertilizer recommendation at right time to farmers and rural youths. Variable rate machineries based on map and sensing system are promising technologies for nutrient assessment and precise fertilizer application for large field. Modern harvesting machineries with pre-installed yield monitor had been developed and commercialized for several crops. Site-specific crop nutrient management technologies can significantly increase agro-input efficiency, agronomical, financial and environmental benefits.

DISCLAIMER

The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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