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Sensor based Monitoring for Improving Agricultural Productivity and Sustainability - A Review

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Soil proximal sensing technologies provide an excellent opportunity for rationalizing input use. This paper critically reviews the current technologies available for soil and crop sensors and suggests effective, economically attractive alternatives for conventional methodologies. It also sheds light on the different types of sensors, including hand-held sensors and soil spectroscopy for precision agriculture. Additionally, this article explores options for drought monitoring and crop yield modelling through remote sensing. An overview of the Decision Support System (DSS), including ICAR Geoportal, is also presented to provide the real-time solution.

Key words: Agriculture monitoring, Decision support system, Precision farming, Soil and crop sensors, Remote sensing

Technological changes during the past century, such as the Green Revolution, have transformed agriculture's face. The improved crop varieties, synthetic fertilizers, pesticides, and irrigation were the key to the green revolution to enhance crop productivity and food security, especially in developing nations. However, India needs about 350 million tonnes (MT) of food grain by 2050 to feed the 1.7 billion of population. Given the limited availability of arable land, a significant part of this increased demand will be met through agricultural intensification, *i.e.*, increased use of fertilizers, pesticides, water, and other inputs. However, intensified use of agricultural inputs such as fertilizers and pesticides cause economic losses and environmental degradation, including groundwater depletion, reduced surface flows, and eutrophication. For an economically and environmentally sustainable production system, there is a need to develop techniques to increase input use efficiency and reduce environmental losses (Sishodia *et al*. 2020). The availability of real-time information is the key to sustainable agricultural management. The conventional methods of laboratory analyses are costly, labour- and time-consuming. On the other hand, proximal, ground-based, and hand-held sensors can rapidly collect high-resolution data and, in some instances, even allow real-time analysis and processing by taking measurements as frequently as once per second. For example, sensor-based soil analysis potentially provides several advantages over conventional laboratory methods, such as lower cost, increased efficiency, rapid and timely results, and collection of dense data sets while traversing a field.

Soil is a vital agricultural resource that must be managed with utmost care and accuracy for sustainable production. Soil properties greatly vary across space and time. The occurrence of soil variability results from dynamic interactions between natural environmental factors. Soil properties and in turn plant growth are significantly controlled by the soil heterogeneity and bio-geo-chemical process and their interactions within soils. Knowledge about the spatial variability of soil nutrients is important for refining agricultural management practices and improving sustainable land use and food production. Improved management of essential plant nutrients is key to achieving sustainable agriculture and

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maintaining necessary food production increases while minimizing economic losses and environmental pollution. Recent advances in crop management strategies indicate that efficient nutrient management in crop fields can be achieved through the precise application of nutrients by diagnosis at the site and applying the required nutrient simultaneously (SSNM). To achieve this, we may harness geospatial technologies such as global positioning systems (GPS), geographic information systems (GIS), remote sensing, geo-statistics, and variable rate applicators for different inputs in agriculture. The variable-rate fertilizer application has been shown to optimize nutrient use efficiency by overcoming the problem of over- and under-fertilization. Ultimately, this strategy is envisaged to increase crop yields and quality, resource use efficiency, and promote environmental stewardship. The development of a detailed site-specific soil resource database is ultimately imperative for the implementation of precision agriculture. It will allow the farmer to produce more efficiently and help economically and efficiently use resources such as water, plant nutrients, and agrochemicals. Characterization of soil variability at the field scale using the conventional approaches is a labor-intensive, expensive, and time-consuming procedure. Therefore, soil sensors and sensing technologies are the need of the hour to quantify the soil nutrient status rapidly on a spatial scale to allow efficient site-specific soil nutrient management and allocation of farm resources wisely and efficiently.

Importance of soil health concept has gained renewed momentum in the past several years. While awareness of soil health is increasing, it is essential to have a good understanding of what soil health entails, how it is measured, and how to manage it for optimal and sustainable delivery of the ecosystem services that soils provide, besides food security and climate resilience. Soil Health Card Scheme under the National Mission for Sustainable Agriculture by the Government of India aims to promote location and crop-specific sustainable soil health management, including the judicious application of fertilizers for improving/sustaining soil health and productivity. For the successful implementation of such missions, rapid and accurate soil testing methods using advanced tools and techniques are needed.

Information on soil nutrient status is vital for optimal crop growth; consequently, this information is the basis for appropriate fertilizer application and management. Soil testing by chemical analysis of soil organic carbon (SOC), nitrogen (N), phosphorus (P), potassium (K), electrical conductivity (EC), and pH levels help to determine the status and availability of the nutrients in the soil. Producers use soil test results along with past soil management practices, irrigation water availability, and cropping history to decide the amount of fertilizers that should be applied. In the current practices of soil testing, the farmers need to collect soil samples, transport them to the laboratory, and get them analyzed in a laboratory, and getting results usually take up to 3 weeks or more. Farmers who implement this practice reap the benefits of having a comprehensive guide to manage their production and economic expenditures better. Farmers also ensure best practices in agriculture and guarantee that nutrient applications are solidly based on real information. It is especially important to reduce pollution and safeguarding both ground and surface water quality, as well as to ensure need-based fertilizer application in fields.

Recently, infrared spectroscopy has been recognized as one of the promising techniques to address the limitations of wet chemistry in handling a large number of datasets. This technique can be used for rapid, cost-effective, and precise assessments of various soil properties. The latest research trends demonstrate considerable effort to develop near-infrared (NIR) and mid-infrared (MIR) methods to rapidly estimate soil parameters. The diffused reflectance spectroscopy (DRS), comprising both NIR and MIR regions, is emerging as a new tool to obtain information on soil and may be an important step in the fast, reliable, and economic estimation of soil characteristics for sustainable management. These techniques do not use environmentally harmful chemicals, require fewer pre-treatments, and, when combined with multivariate calibrations, a single spectrum can provide estimates of a number of soil properties. The techniques are highly sensitive to both organic and inorganic soil composition, making them potentially useful and powerful tools for assessing and monitoring soil and its quality.

Variable rate application of nutrients is typically based on a rigorous sampling regime and time-consuming data analyses. The ability to monitor soil nutrient concentration efficiently is highly desirable. The approach includes onsite monitoring of soil nutrient concentration which offers an opportunity for higher density measurements at relatively lower costs. This would allow for efficient mapping of nutrient variability to facilitate variable-rate nutrient application. Implementing nutrient management programs using sensor technology promotes environmental stewardship while maintaining crop productivity and profitability. Rapid and non-destructive quantification of spatially-variable soil nutrients has been made possible with on-the-go sensors such as optical, electromagnetic, and electrochemical sensors.

Sensors for Automated Measurements

Recent advances in sensor technologies indicate that efficient nutrient management in crop fields can be attained through the application of precision agriculture (PA)-based geospatial technologies such as GPS, GIS, remote sensing, geo-statistics, and variable rate application. Variable-rate fertilizer application for site-specific nutrient management (SSNM), one of the basic tenets of PA, has been found to optimize fertilizer use efficiency by overcoming the problem of over- and under-fertilization. The development of cost-effective SSNM strategies is envisaged to increase crop yields and quality, reduce resource waste, and control environmental pollution. Spatial and temporal variability in crop and soil productivity is influenced by both intrinsic (*e.g.*, soil forming factors such as parent material, climate, topography, fauna/flora and time) and extrinsic factors (*e.g.*, farm management practices and maintenance operations). Quantifying the spatial and temporal variability of soil properties and responding to such variability via the carefully designed site- and time-specific input application is believed to enhance nutrient assimilation in crops and consequently enhance their use efficiency. Soil sensors and sensing technology are needed to quantify the soil health status rapidly on a spatial scale to allow efficient site-specific soil nutrient and water management and allocation of farm resources wisely and efficiently. The conventional laboratory methods may offer highly accurate analysis of soil. However, *in situ*-based soil nutrient sensors that offer real-time feedback are needed to increase the efficiency of farming and managing the environment.

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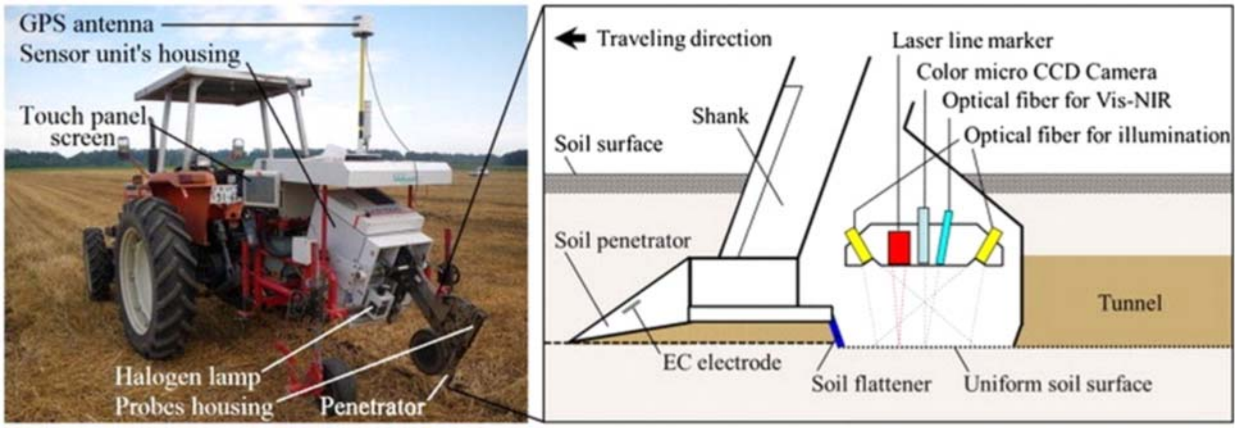

Fig. 1. Schematic view of on-the-go sensors

optical, mechanical, electrochemical, airflow, and acoustic have been investigated to estimate different soil physical and chemical properties.

Electrical and electromagnetic sensors

They use electric circuits to measure the capability of soil particles to conduct or accumulate electrical charges. When using these sensors, the soil becomes part of an electromagnetic circuit and changing local conditions immediately affect the signal recorded by a data logger. Electromagnetic soil properties, for the most part, are influenced by soil texture, salinity, organic matter, and moisture content. In some cases, other soil properties such as residual nitrates or soil pH can be predicted using these sensors.

Optical/radiometric sensors

These sensors use light reflectance to characterize soil. The principle of this approach is the interaction between incident light and soil surface properties, such that the reflected lights vary as a function of the soil physical and chemical properties. Optical nutrient sensing techniques are non-destructive and often more favored than electrochemical sensing. In optical sensing of soil, the visual, near- and mid-infrared spectral reflectance can potentially estimate texture, moisture, cation exchange capacity, pH and other soil parameters if proper data analysis techniques are applied. Vehicle-based optical sensors use the same principle/technique as remote sensing. Close-range, subsurface, vehicle-based optical sensors have the potential to be used on the go, in a way similar to electromagnetic sensors, and can provide more information about single data points since reflectance can be easily measured in more than one portion of the spectrum at a time.

Electrochemical sensors

These sensors could provide the most important type of information needed for precision agriculture — soil nutrient levels and pH. Soil properties here are measured using either anion-selective electrode (glass or polymer membrane), or anion-selective field effect transistor (ISFET). This approach measures the potential voltage difference between sensing and reference parts of the system, which relates to the concentration of specific ions (*i.e.* H^+, K^+, NO_3^-). Ion-selective membrane sensors offer opportunities for on-the-go soil nutrient(s) and pH measurements (Schirrmann and Domsch 2011).

Presently, the limitation of the technology is that the values obtained may not be as accurate as a laboratory test, but the high sampling density may increase the overall accuracy of the resulting soil nutrient or pH maps. In the future, on-the-go electrochemical sensing may allow for cost-effective monitoring of heterogeneous soils at high sampling resolution. There has been considerable progress with applying on-the-go soil nutrient sensing based on ion-selective electrode technology.

Mechanical sensors

They can be used to estimate soil mechanical resistance (often related to compaction). These sensors use a mechanism that penetrates or cuts through the soil and records the force measured by strain gauges or load cells. Draft sensors or “traction control” system on tractors uses a similar technology to control the three-point hitch on the go.

Soil Spectroscopy

Soil spectroscopy has emerged as a promising technology for soil testing/analysis/health assessment towards efficient management of essential plant nutrients and water. Compared to traditional wet chemistry - soil analysis, which is time, energy and cost-intensive to meet the huge data requirement goals, this new technique of soil spectroscopy is fast, cost-effective, environment friendly, and repeatable. The technology being used in labs has now started being used as portable hand-held devices too.

Soil visible–infrared sensing could be an alternative to laboratory analyses of soil attributes such as organic and inorganic carbon, pH, total N, water retention characteristics, texture, and mineralogy (Nocita *et al.* 2015). The processing of the sample if required is simple and a number of parameters can be estimated simultaneously from a single spectrum. Measurements are reproducible, and results can be obtained much cheaper. Thus, soil spectroscopy can play an important role in large volume spatially intensive analysis of soil parameters. Off-late, there is growing interest in soil spectroscopy with improvement of visible–near-infrared (VIS, NIR) and mid-infrared (MIR) spectrometers, increase in the computational power of computers, and advancement of computer-based statistical/ chemometric analysis tools (Fig.2). Large databases of soil spectra are being developed to meet the growing demand for soil information to assess and monitor soil at various scales (Viscarra Rossel and Bouma 2016). Among the different infrared spectroscopic techniques in use, the

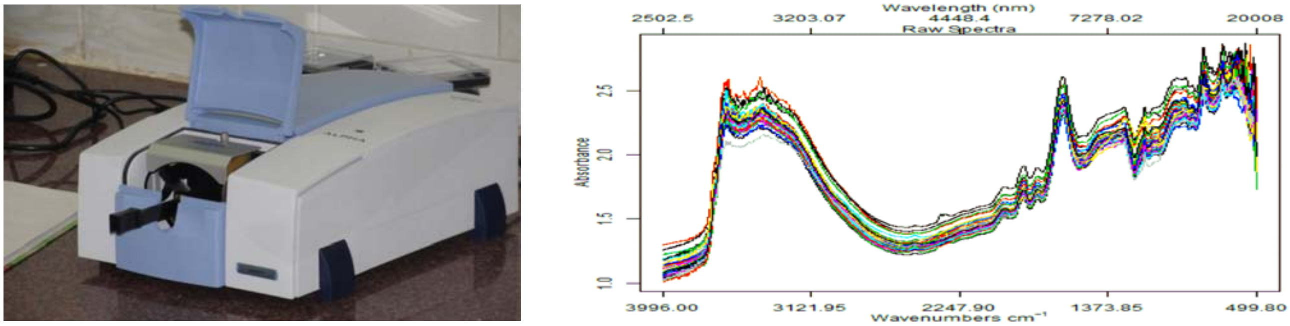

Fig. 2. FT-MIR spectrometer and MIR Absorption Spectra

MIR based instruments are generally considered more accurate compared to the NIR spectroscopy because the MIR region is dominated by intensive fundamental vibration, whereas the NIR region is dominated by much weaker and broader signals from vibration overtones and combination bands (Ludwig *et al.* 2008). Sophisticated statistical techniques are used for quantitative spectral analysis of soils using reflectance spectroscopy to uncover the response of soil attributes from spectral characteristics. Chemometric methods are applied to extract information mathematically from the pre-processed soil spectral data. The information extracted is then empirically related to conventional laboratory measurements to build the MIR calibration models (Xia 2016). There is a need to develop region or soil type-specific prediction models using regional soil spectral library with laboratory analyzed soil parameters value for more robust and reliable prediction. Identification of important spectral bands in the MIR and NIR region contributing towards predicting soil parameters is required as these spectral regions can be used to develop cost-effective sensors for in-situ and sometimes on-the-go estimation of soil fertility status.

With the advancement of optics and electronics circuits, spectrometers are becoming cheaper, smaller, and more accessible, and consequently, proximal soil sensing has become more viable. New technologies that use micro-electro-mechanical structures (MEMSs), thin-film filters, lasers, light-emitting diodes (LED), fibre optic assemblies, and high-performance detector arrays are being used to produce miniaturized hand-held instruments that are rugged and cheap. Measurements can be made on moist soil, *i.e.*, *in-situ* under field conditions, removing the need for sample drying, grinding, and other preparations using hand-held VIS-NIR based spectroscopy (Parikh *et al.* 2014). Besides the visible-IR-based spectrometers, the *X-ray fluorescence* spectrometers can also be used to measure the total elemental composition of soil macro- and micronutrients and heavy metal composition, conducting studies on colloidal transport, soil compaction, and soil consolidation by wetting and drying cycles. Besides this, another promising method, which is potentially well suited for in-field determination of total contents of elements in soils, is laser-induced breakdown spectroscopy (LIBS), an optical emission spectroscopy technique. LIBS-based technique can be potentially used for simultaneous multi-element analysis of soil. In comparison to X-ray fluorescence (XRF), the whole range of elements, including light elements like N, is measurable by LIBS. Thus, LIBS appears particularly well suited for the spatial scale's high-density soil analysis of agricultural fields (Erler *et al.* 2020). However, instruments developed for rapid and non-destructive measurement of soil health parameters using diffused reflectance spectroscopy are yet to come into a commercial stage. Many promising technologies are being tested to develop on-the-go variable nutrient applicators for site-specific nutrient management.

Hand-held sensors for precision agriculture

Many sensing technologies such as micro-electro-mechanical structures (MEMSs), thin-film filters, lasers, light-emitting diodes (LED), fibre optic assemblies, and high-performance detector arrays are being used to produce miniaturized hand-held instruments in agriculture (Coates 2014). These systems are rugged and cheap. They can be incorporated into mobile telephones. Périard *et al.* (2016) reviewed the use of X-rays for monitoring time-dependent changes in soil properties such as bulk density, tortuosity, porosity, pore network characteristics, permeability, volumetric water content, solute transport parameters, fractal properties, soil aggregate characteristics, unsaturated hydraulic conductivity, and soil water retention curves. Besides

Fig. 3. Hand held sensors for nitrogen management and sensor-based herbicide applicator

this, rapid and non-destructive quantification of spatially-variable soil nutrients, mostly N, can be made possible through on-the-go or hand-held sensors using optical, or electromagnetic sensors (Fig. 3). These sensors could be handy for SSNM as the crops' nutrient need varies from year to year and field to field. Precisely matching N-fertilizer rates to crop needs maximizes benefits while reducing negative impacts. Crop reflectance sensors provide an accurate and spatially intensive method for diagnosing and applying the correct N rate during standing crops. Reflectance sensors allow real-time measurement of crop spectral properties with nearly immediate translation into N rate decisions. Some of these sensors are Soil Plant Analysis Development (SPAD) 502 plus (KonikaMinolta®Inc., Tokyo, Japan) and at LEAF (FT Green LLC®, Wilmington, DE, USA), Crop scan (Crop scan Inc., Rochester, MN, USA), Crop Circle (Holland Scientific, Lincoln, NE, USA), and Green seeker (NTech Industries, Ukiah, CA, USA) (Table 1). These hand-held reflectance sensors can easily be calibrated to predict the optimal N fertilizer rate in different crops. Studies showed that as much as 20% of inputs could be saved using these hand-held sensors for precise N management. Further, green seekers, through NDVI calculation, can also be used to assess overall crop health, leaf area, biomass, yield, and nutrient response.

Early weed control is vital in successful crop production. Most weeds are either controlled mechanically by some form of cultivation or chemically by applying herbicides. Of the vast tonnage of chemical herbicides applied, a large proportion is lost because of drift or evaporation, deposited on the crop or the soil, and only a low percentage of the herbicide reaches the target weeds. Therefore, there is a need for site-specific weed control technologies that act autonomously to maximize the chances of detecting, selecting measures, and controlling weeds in a given crop at a given growth stage (Christensen *et al.* 2009).

They further suggested three elements of site-specific weed control technologies:

- A weed sensing system, identifying, localizing and measuring crop and weed parameters.
- A weed management model, applying knowledge and information about the crop-weed competition, population dynamics, biological efficacies of control methods and decision-making algorithms, and optimizing treatments according to the density and composition of weed species, economic goals and environmental constraints.
- A precision weed control implement, *e.g.*, a sprayer with individual controllable boom sections or a series of controllable nozzles that enable spatially variable applications of herbicides

Table 1. Innovations in proximal leaf sensing used to guide fertilizer N management in precision agriculture (Adapted from Singh and Ali 2020)

Year of innovation	Hand-Held Sensor
1992	SPAD chlorophyll meter (transmission of 650, 940 nm), used to detect N deficiency and estimate fertilizer N.
1995	Nitrogen sufficiency indices (ratio of SPAD meter readings of the test plot and that of a well-fertilized or N-rich reference plot).
1996	Canopy reflectance sensor (reflectance of 671, 780 nm) for detection of variability in plant N stress.
2002	GreenSeeker canopy reflectance sensor (reflectance of 650, 770 nm)
2004	Crop Circle canopy reflectance sensor (reflectance of 590, 880 nm or 670, 730, 780 nm).
2012	Leaf chlorophyll meter (transmission of 660, 940 nm)

Rueda-Ayala *et al*. (2015) proposed a non-chemical weed control system. It adjusts the tine angle of a harrow and creates different intensity levels to compete with the conventional herbicide. An ultrasonic distance sensor is also developed to detect site-specific weed management. It is working on the principle that weed-infested zones have a higher amount of biomass than non-infested areas and that this can be determined by plant height measurements (Andújar *et al.* 2012). A broad range of equipment is available for weed identification, quantification, decision-making and robotic systems based on ground or satellite operation (Christensen *et al.* 2009; López-Granados 2011).

Digital Soil Maps of Micro-Nutrient Status of the Country

Injudicious use of macronutrients coupled with the absence of micronutrients in soil nutrient management is a major constraint in achieving food and nutritional security for India's ever-increasing population. With the intensive cropping of high-yielding varieties of rice and wheat, deficiency of zinc (Zn) initially and subsequently deficiencies of iron (Fe) in rice, and manganese (Mn) in wheat, emerged as threats to sustaining high levels of food crop production. Analysis of soil and plant samples has indicated that 49% of soils in India are potentially deficient in Zn, 12% in Fe, 5% in Mn, 3% in copper (Cu), 33% in boron (B) and 11% in molybdenum (Mo) (Singh 2008).

Efforts to delineate micronutrient deficiency are an uninterrupted activity of the project of AICRP on Micro- and Secondary Nutrients and Pollutant Elements. During 2011-2017, an analysis of more than 200,000 soil samples collected with the help of GPS from 538 districts of the country revealed that on an average of 40.5, 36.5, 12.8, 7.1, 4.2, and 23.2% of soils are deficient in S, Zn, Fe, Mn, Cu, and B, respectively (Shukla and Tiwari 2016). About 1.94 lakh soil samples were georeferenced to prepare a soil map of micronutrients. From 2011 onwards, soil maps of micronutrients of 58 Agroecological sub-regions (AESRs) out of the total 60 AESRs have been prepared. These digitized maps of micronutrient status will be highly useful in understanding the nature and micronutrient problems in India besides formulating strategies to alleviate their deficiencies and help policymakers and industries to produce and distribute the right kind of micronutrient fertilizers in different agroecological regions. These maps will also enable the specific variable rate of application. They will also provide the basis for site-specific decision for policy makers for a prudent and balanced micronutrient management.

Spatial distribution of micronutrients in the country

Zinc deficiency

Zinc deficiency is the most widespread micronutrient deficiency in the country (Fig. 4). Extent of Zn deficiency varied among states from as low as 9.6% in Uttarakhand to as high as 75.3% in Rajasthan. By and large, extent of Zn deficiency was higher in the states of Rajasthan (75.3%), Madhya Pradesh (66.9%), Tamil Nadu (65.5%), Maharashtra (54.0%), Bihar (44.0%) and Uttar Pradesh (33.1%). Among the AESRs, Zn deficiency is highest in Marusthali hot, hyper arid AESR (76.9%) followed by Tamil Nadu Upla (73.3%) and Malwa Plateau (68.8%). Zn deficiency is found in soils that are coarser in texture, high pH, low organic matter or calcareous.

Iron deficiency

Iron deficiency was more acute in the western parts of the country, particularly Rajasthan, Gujarat and Maharashtra. It is also coming up in Telangana, Karnataka, Uttar Pradesh and Bihar. The problem of Fe deficiency is mainly in calcareous and other alkaline soils having pH > 7.5. The availability of Fe gets reduced under drought or moisture stress condition due to conversion of Fe^{2+} form to less available Fe^{3+} form. On the other hand, the soils of north-eastern districts, Odisha and Kerala are reported to have Fe toxicity problem in rice paddies. In Assam, deficiency was absent whereas it was negligible is acid soils of West Bengal, Jharkhand, J&K, Mizoram, Himachal Pradesh, Kerala, Meghalaya, Uttarakhand, Arunachal Pradesh and Tripura. Among the AESRs, Fe deficiency is widespread in the Western Plain where 645.9, 60.0, 40.5 and 45.7% of soils in the Marusthali hot (2.1), Kachchh Paninsula (2.2), Rajasthan Bagar and South Kachchh AESRs are deficient in Fe, respectively (Shukla and Tiwari 2016).

Manganese deficiency

Manganese deficiency in Indian soils is relatively low in comparison to other micronutrients, with Cu being exception. Out of 536 districts, 396 districts exhibited very high available Mn content. Thirty-six districts showed more than 25% soil samples to be Mn-deficient. Mn availability is influenced by soil moisture, and affects the incidence

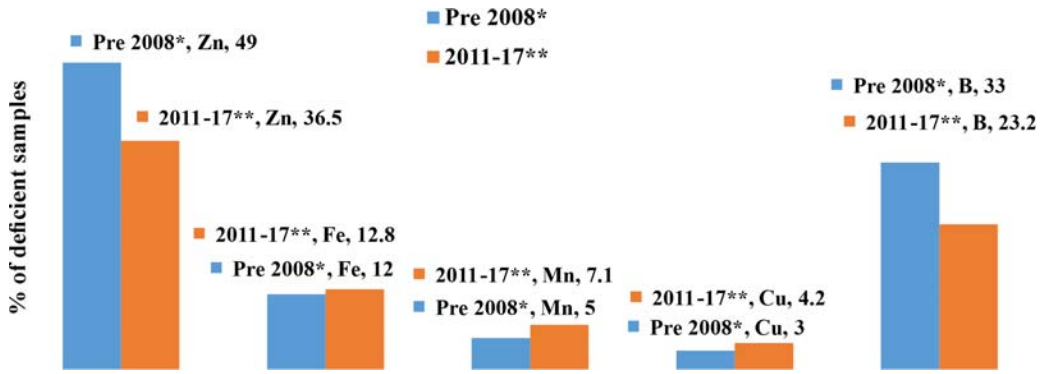

Fig. 4. Micronutrient deficiency in Indian soils (*Singh 2008; **Shukla and Behera 2019)

and severity of Mn deficiency in crops grown with low moisture content. Mn deficiency was highest in Rajasthan (28.3%). Among the AESRs, maximum deficiency is found in Marusthali hot (38.9%), Punjab and Rohi (28.4%), North Punjab Plain (24.4%), Kachchh Peninsula (15.9%) and Foothills of Central Himalayas (17.9%).

Copper deficiency

Copper deficiency is not a major concern showing deficiency in 4.2% soils only. Of the 536 districts delineated for Cu deficiency, soils of only 38 districts showed more than 10% samples to be Cu-deficient. Except Tamil Nadu (12.0%), Rajasthan (9.15%), Odisha (8.32%), and Haryana (5.13%), Cu deficiency is negligible in other states. Among the AESRs, highest deficiency was found in Marusthali hot (20.6%), followed by South Tamil Nadu (23.8%) and Eastern Ghats (13.4%). The Cu deficiency is mostly confined to sandy, calcareous, eluviated and organic-rich soils.

Boron deficiency

Extent of B deficiency in India is next only to Zn. More than 30% B deficiencies are reported from calcareous soils of Bihar (39.5%), acid soils of West Bengal (37.1%), Assam (32.7%), Himachal Pradesh (33.6%), Kerala (31.2%) and Maharashtra (35.5%). Among the AESRs, more than 50% deficiency is present in South Western Maharashtra and Karnataka (55.0%) and deep loamy red and lateritic soil of Chottanagpur Plateau and Gajrat Hills (59.5%). In general, B deficiency is higher in eastern region and has resulted due to its excessive B leaching in sandy loam soils, alluvial and loess deposits. By and large, B deficiency is more critical to sustainable production in highly calcareous soil, leached soils, limed acid soils or reclaimed yellow or lateritic soil.

Molybdenum deficiency

Most of the soils are adequate in Mo but its deficiency is noticed in some acidic, sandy and leached soils and it is localized in some parts of Maharashtra, Odisha and West Bengal, Kerala and Himachal Pradesh (Shukla and Behra 2019). However, since only a small number of soil samples were analyzed, the data cannot be used to delineate the soils of any state for available Mo.

Digital Soil Maps of Phosphorus

Phosphorus, an essential plant nutrient, plays a major role in growth and development of plants. It is incorporated into different biomolecules, including nucleic acids (DNA and RNA), phosphor-proteins, phospholipids, sugar phosphates, enzymes, and energy-rich phosphate compounds such as ATP. The total P concentration in agricultural crops generally varies from 0.1 to 0.5% below which distinct deficiency symptoms are visible. Insufficient P in plants leads low yield and quality, and crop yield loss due to P deficiency is estimated at 30–40%. In soil, P exists in four different pools based on its accessibility and extractability such as soil solution P; surface-adsorbed P; strongly-bonded or absorbed P; and very strongly–bonded or inaccessible or mineral or precipitated. The soil solution P is immediately available for uptake by plant roots. The second pool represents readily extractable P held on the surface of soil components. This pool is considered to be in equilibrium with soil solution P, and can be transferred readily to the soil solution as the concentration of P in the latter is lowered due to P uptake by plant roots. Although soil total P may be generally high, it is poorly correlated with the plant available P. Phosphorus occurs in soil predominantly in the inorganic form, although organic forms of P may also contribute substantially (20–80%) to the total

Table 2. Fertility status of phosphorus in Indian soils from different studies

Year	District studied	Samples (millions)	P fertility status[@] (%)			Reference
			Low	Medium	High	
1969	226	1.3	47.0	49	4	Ramamoorthy and Bajaj (1969)
1979	363	9.2	46.0	52	2	Ghosh and Hassan (1979)
1996	-	9.6	49.3	48.8	1.9	Hasan (1996)
2002	307	3.7	42.3	37.7	11.3	Motsara (2002)
2011	500	-	49.0	45.0	6.0	Muralidharudu *et al.* (2011)

[@]A soil analyzing less than 10 kg P ha^{-1} (Olsen-P value) is categorized as low, between 10 to 25 kg P ha^{-1} as medium, and over 25 kg P ha^{-1} as high in P availability

P content. In Indian soils, inorganic P generally contributes 54–84% of total P, whereas the share of organic P varies from 16–46% in different states.

Compilation based on several findings showed that plant available P in the surface of arable soils was low in available P content (Table 2). Earliest soil test summaries by Ramamoorthy and Bajaj (1969) and later by Ghosh and Hasan (1979) suggest that only 2-4% of our soil have adequate soil available P. Soil-P fertility map for the country was first published in 1979 and was updated based on 9.6 million soil test summaries in 1993 by Hasan (1996). In this study, about 49.3% of the districts and union territories were low, 48.8% medium, and 1.9% high in available P. Compared to an earlier test summaries prepared by Ghosh and Hasan (1979), Hasan (1996) reported that samples in low fertility class increased by 3.3%, while the medium categories exhibited a decrease of 3.2%.

The GIS based district-wise soil fertility maps from 500 districts of India (Muralidharudu *et al.* 2011) generated during the period from 1995-2008 showed that 49% districts were low, 48% were medium and 6% districts were high. Comparison of zone-wise available P status showed that soils of about 78% district in north zone, 52% in west zone, 38% district in east zone and 51% districts in south zone were low in available P. Only 8, 5, 4 and 22% districts in the north, west, east and south zone, respectively were high in available P. In the north zone, high P soils are concentrated in Punjab and one district of Himachal Pradesh. In Punjab, 50% each of the districts are medium and high in available P. In west zone, high available P is found in 6 districts of Madhya Pradesh *viz*., Guna, Rajgarh, Dhar, Sehore, Hoshangabad and Dinori. In east zone high available P is found in Hoogly and Lohardaga districts of West Bengal and Jharkhand state, respectively. The south zone except Andhra Pradesh is more fertile in terms of available P. Here, 30 districts out of the total 94 districts fall under low P category. Hasan (1996) reported that generally the deep black, grey brown, desert and red loamy soils of semi-arid regions were medium with respect to P-fertility. Thus, P deficiency in Indian soils is most widespread in north, followed by west, east and south zone soils. Application of adequate P fertilizers is highly profitable and is of paramount importance to ensure food security of the country.

Latest study on GPS and GIS-based soil fertility appraisal carried out for 173 districts of the country registered wide variation of P status (Dey *et al.* 2017) Fertility mapping of eleven high fertilizer consuming districts of Tamil Nadu clearly brought out the fact that nine districts fell under ‘high-P’ and two districts under ‘medium-P’ category. Further, even under acid soil regions of Thrissur, Kozhikode, Ernakulam and Alappuzha districts of Kerala were found to have high in available P content. However, available P content in coastal district of Puri in Odisha was found to vary from low to medium ranges. GPS/GIS based soil fertility mapping of nine districts of Karnataka, showed very wide variability; higher values were found in Tumkur, Kolar, Chikkaballapura and Hassan districts.

Soil texture map of India

Soil is a dynamic and complex system of air, water, decomposing organic matter, living plants and animals. In addition to this, soil consists of rock fragments, clays, sands and silts organized into definite pattern as dictated by environmental conditions. These physical properties of the soils influence the chemical and biological properties of the soils and it is of utmost importance in relation to plant growth as well as soil fertility.

Soil texture (proportion of sand, silt and clay) is the most important soil physical property that determines water holding capacity, nutrient availability and crop growth. Spatial distribution of soil texture at a higher spatial resolution at regional and national level is essential for crop planning and management. Conventionally, soil texture is determined in the field by feel method and further confirmed by laboratory analysis of particle size fractions using international pipette method or hydrometer method. These methods are expensive; require a large number of samples to obtain the spatial distribution of soil texture over large areas at a higher resolution. Digital soil mapping technique overcomes this problem by prediction of soil properties and soil classes based on quantitative soil-landscape models.

The digital soil map (DSM) for sand and clay contents in the root zone depth of 0–30 cm showed that the western Indian states of Rajasthan and parts of Gujarat, Punjab and Haryana showed high sand contents under the prevailing hot and arid climate with limited rainfall (Reddy *et al.* 2021). The reverse is true for clay contents for this region in addition to the areas covering the upper Indo-Gangetic basin (Fig. 5). High clay contents are primarily in the central Indian states of Madhya Pradesh, Maharashtra, and western parts of Karnataka. Basaltic parent material and low rainfall in the Bastar and Dharwar regions covering these states led to the formation of black cotton soils with vermicullitic and illitic clays while the aeolian deposits in the far western Rajasthan had weakly developed soil profiles with high sand content. Prevailing high rainfall and high temperature with granitic parent material in the eastern Indian regions have led to the formation of moderate to strongly weathered soils with a dominance of kaolinitc clays with different intergrades of smectites.

Across different agroecological regions, the DSM showed that the Western Plains (AER 2) contained the largest share of sandy soils with clayey soils dominated in the central Deccan Plateau (AER 6). Almost half of the AERs showed > 40% clay content in top 2 m soil profile signifying moderate to strong weathering conditions promoted by high temperature and high rainfall across the country. These maps of may be linked to soil productivity and provisioning of ecosystem services to guide policy makers for creating region-specific soil management plans.

Drought monitoring and crop yield modelling through remote sensing

Information on the receipt of rainfall, drought monitoring, and crop yield estimation during crop season is crucial from policy and implemental aspects (Fig. 6). The advent of advanced technology, especially satellite-based, helps quantify the weather variables and crop growth information in real-time with limited human interference and wider coverage. The derived information from satellite-based sensors can be linked with crop growth models as input for further crop yield estimation.

Rainfall, the key driver of the hydrological cycle and river/stream flows, plays an important role in crop production as dry spells affect crop growth and yields during the crop season. Failure in rainfall leads to drought conditions. Hence, estimation of rainfall on a real-time basis is one of the crucial aspects in drought

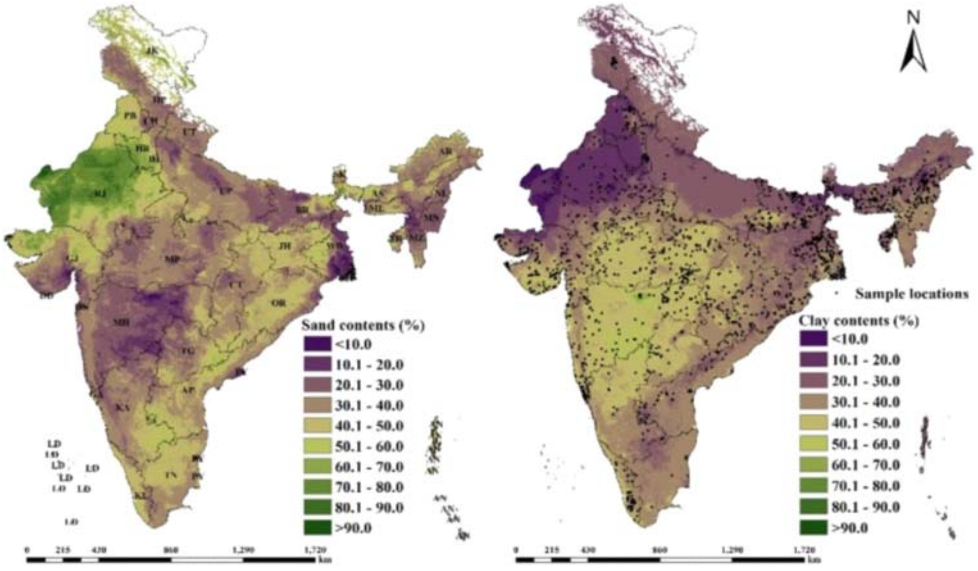

Fig. 5. Sand and clay content map of India
(*Source:* Reddy *et al.* 2021)

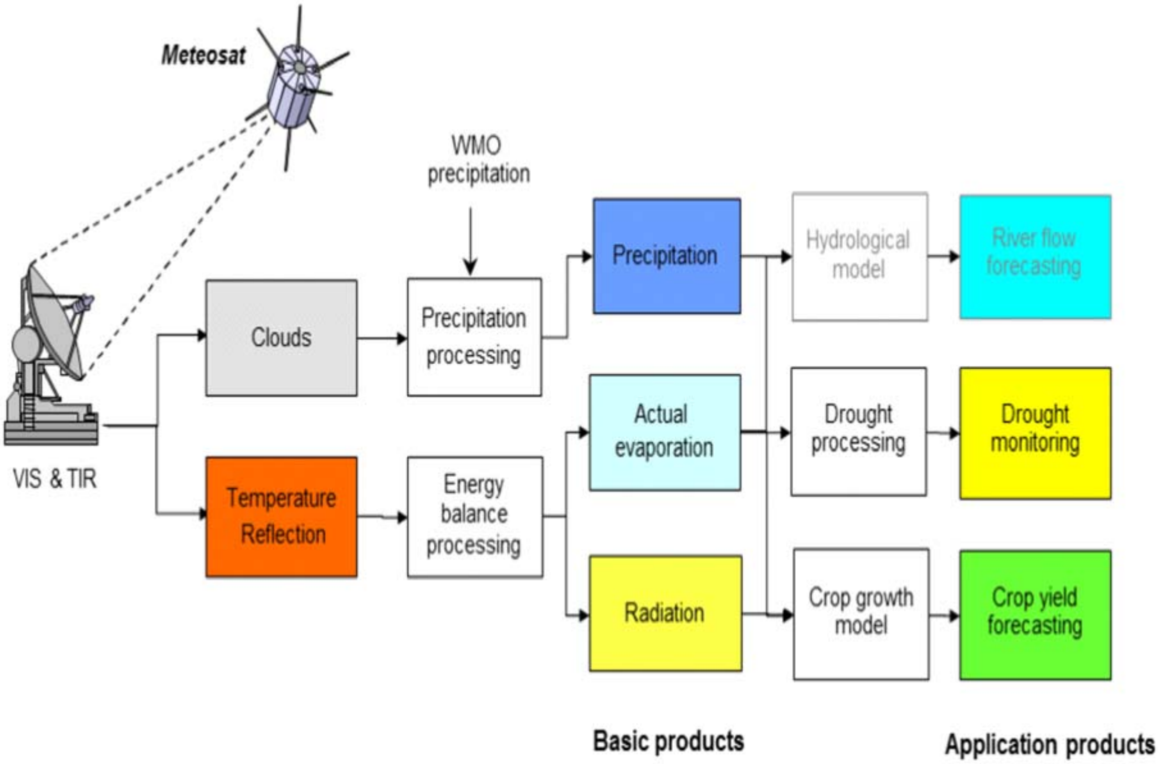

Fig. 6. Flow diagram of remote sensing-based weather forecasting and modelling for yield prediction

forewarning and crop yield prediction. Several studies have been undertaken to standardize the procedure to estimate rainfall using satellite products.

However, due to the indirect nature of the observations, the satellite-derived rainfall products can be affected by large errors (Kucera *et al.* 2013) and have difficulties in estimating the accumulated rainfall due to the instantaneous nature of measurements (Brocca *et al.* 2016). A novel "bottom-up" approach by Brocca *et al.* (2016), uses soil as a natural rain gauge by finding the variations in soil moisture (SM) sensed by microwave satellite sensors to infer preceding rainfall amounts.

Large volumes of water from soil and vegetation transfers through land surface evapotranspiration (ET) to the atmosphere. The differences between the actual and potential ET at high spatial resolutions are of interest to agriculture, water resources, and as an indicator of crop water deficits which helps in drought monitoring. A satellite-based image-processing model has been developed (Allen *et al.* 2007). It has a process component of "Mapping evapotranspiration at high resolution with internalized calibration (METRIC)" for calculating evapotranspiration (ET) as a residual of the surface energy balance. METRIC uses as its foundation the pioneering SEBAL energy balance process developed in The Netherlands by Bastiaanssen *et al*. (1998). The ET is generally determined from satellite imagery by applying an energy balance at the surface, where energy consumed by the ET process is calculated as a residual of the surface energy equation;

$$LE = Rn - G - H$$

where, LE=latent energy consumed by ET; Rn=net radiation _sum of all incoming and outgoing short wave and long-wave radiation at the surface; G=sensible heat flux conducted into the ground; and H=sensible heat flux convected to the air.

An evaluation and comparison study using the climate prediction center morphing (CMORPH) technique (CMORPH-CRT), tropical rainfall measuring mission (TRMM) multi-satellite precipitation analysis (TRMM 3B42V7), and the integrated multi-satellite retrievals for global precipitation measurement (IMERG V05) rainfall products for the drought monitoring in the Xiang River Basin was done in the humid region of China (Zhu *et al.* 2019). To evaluate the drought monitoring utility, a standardized precipitation index (SPI) was considered and found that IMERG V05 showed the best performance in SPI-1 (one-month SPI) drought estimation (Parihar and Oza 2006). In India, drought assessment for 13 states was carried out under National Agricultural Drought Assessment and Monitoring System (NADAMS) project using remote sensing data from multiple sources integrated with the ground and meteorological information at district/sub-district level.

Prediction of agricultural crop yields is one of the important tasks for the government to plan for the storage of the produce, market creation, import/export of the produce etc. Yield is influenced by many factors such as soil characteristics, variety, irrigation, fertilizer and weather (*i.e.* temperature, sunshine hours etc.). Spectral data provides an integrated effect of all these factors (Parihar and Oza 2006). Weather variables are often used in conjunction with spectral data to model yields.

The use of remote sensing data for pre-harvest crop production forecast has been operationalized in India under Forecasting Agricultural output using Space, Agrometeorology and Land based observations (FASAL) funded by the Ministry of Agriculture (Ray *et al.* 2014). FASAL was implemented in the country to make a national-level forecast for crops like rice, wheat, cotton, sugarcane, rapeseed/mustard, rabi-sorghum, winter-potato, and jute. Multiple satellite products, weather data, crop information, and ancillary data to simulate the crop growth models to forecast the production for that season (Parihar and Oza 2006). Vegetation indices and weather parameters derived from surface and satellite observations are used to develop the crop growth monitoring system.

Remote sensing-based technology is used to extract basic weather variables such as rainfall, temperature, and radiation. These variables can be processed to estimate products like ET, drought indices, *etc*. Both the basic and derived weather parameters and crop information (NDVI based LAI) can be fed into crop growth models to forecast crop yields (Fig. 5). Similarly, the same derived information may also be used to monitor the drought situations and implement contingency measures/insurance compensations, *etc*.

Improving Crop Productivity and Profitability through Precision Farming using GIS, GPS and RS techniques

Precision agriculture or site-specific crop management is a farming management concept based on observing, measuring, and responding to inter and intra-field variability in crops. Precision farming uses different inputs required for agriculture, *viz*. land, nutrients, pesticides, seeds, water, and energy in a sparingly and strategic way to improve crop productivity and resource use efficiency, reduce costs, and cause minimal environmental impact. In many developing countries, there is little to no use of precision agriculture technology. There are reasons on almost no adoption of precision farming technologies in India as narrated below.

- More than 60% of operational holdings in India have a size of < 1 ha. The small farm size is one of the reasons for the non-adoption of precision farming technologies in India.
- Appropriate and adaptable precision farming technologies are not available for small to large land holdings in the context of the Indian situation, and there is a need to develop adaptable and affordable technologies.
- The precision farming technologies is data intensive; traditionally, there has been poor data recording and keeping. It may take several years before we have sufficient data to fully implement the system unless this is taken in mission mode like soil health cards.
- Initial capital costs could be high; hence, precision agriculture should be looked at as a long-term investment rather than the technology that would provide immediate results.
- Precision agriculture is extremely demanding work to begin with, particularly collecting and then analyzing the data; developing the hardware and software; and capacity building.

Nevertheless, Indian farming always responded to any demanding scenario; consider green, blue and white revolutions and lived to the stakeholders' expectations. In the same way, precision farming that has the potential to enhance crop productivity and resource use efficiency multifold; cause minimum environmental hazards; make the agriculture climate resilient, and contribute to the National missions, including doubling farm income, can also contribute to enhance the agriculture growth of the country on a sustainable basis. The encouraging factors behind this silver lining are the huge IT knowledge base and human resources required for precision farming; the rapid pace at which sophisticated technologies such as robots, temperature and moisture sensors, aerial images, GPS, drones, and IoT technologies are being developed; and the positive attitude of policy and decision makers to synchronize the traditional farming with the advanced farming for the betterment of the farmers.

The development of any precision farming framework involves the following four stages:

1. Measurement and documentation of the field (land, soil, crop, weather…), variability (RS, GIS, GPS, Sensors)
2. Analyzing the variability for the efficient application of inputs; and their quantification as per variability (Spatial Decision Support System-SDSS)
3. Devices for the application of the inputs as per variability (Variable rate applicators, automation)
4. The communication network (cloud, Wi-Fi, GPRS, drones)

The conceptualization of this framework has been provided by many. Few amongst them are shown in Figs. 7, 8 and 9.

Importance of RS, GIS and GPS technologies for Precision Agriculture

Precision agriculture provides the tools and technologies for identifying the variability in soil and crop of a farm and thus offering means for optimizing crop productivity on a sustainable basis. These tools and technologies include sensing technologies (both

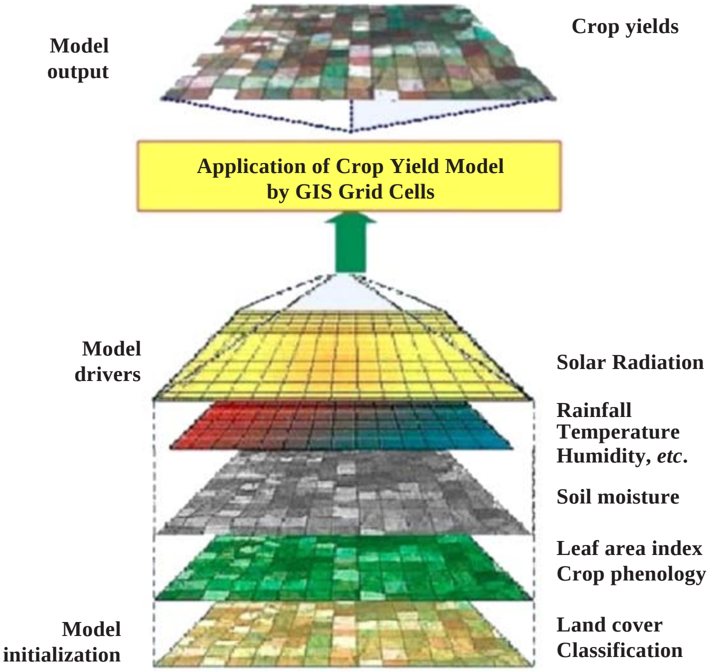

Fig. 7. Flow diagram for remote sensing and model-based yield prediction

Fig. 8. General conceptualization for precision farming mostly adopted in developed Nations with very large farms sizes (https://krishijagran.com/agripedia/precision-agriculture-producing-more-with-less/)

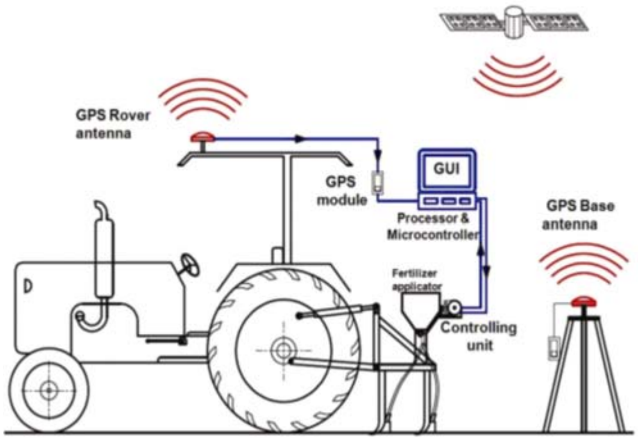

Fig. 9. General conceptualization for precision farming that could be adopted in developing countries (Chandel *et al*. 2016)

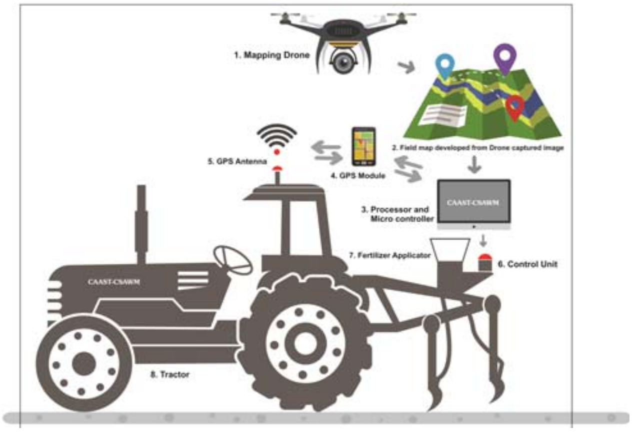

Fig. 10. General conceptualization for precision farming that could be adopted in India (ICAR-NAHEP supported CAAST project on Climate Smart Agriculture and Water Management being implemented at MPKV, Rahuri)

ground-based and remote) for capturing field-level data. Remote sensing uses the interaction between electromagnetic radiation and soil or plant surfaces that depict different responses and enable to identify the surfaces with biotic and abiotic stresses and thus in-field variability. The maps consisting of crop parameters *viz.* crop growth, crop diseases, weeds, crop nutrient deficiencies; soil parameters *viz.* soil texture, chemical and physical properties; and land parameters such as topography and soil depth are required for precision agriculture. As a result, the information depicting crop, soil and land variability through remotely sensed images acquired by sensors mounted on satellites, aircraft, drones or ground-based equipment have become an integral part of precision agriculture. A GIS is a framework for storing, managing, and analyzing data is an integral part, while the GPS enables to accurately navigate to specific locations in the field and to collect the geo-referenced data and monitor. Thus, RS, GIS and GPS technologies together for precision agriculture constitute the first stage of precision agriculture (Figs. 9 and 10).

Variation in Soils and Crops

Important characteristics of land, soil, and crop that influence crop production, often vary considerably over space and time within a single agricultural field (Fig. 11 and 12). Spatial variation in crop performance can be caused by variable soil properties, abiotic and biotic stresses caused due to diseases, weeds, pests, heat, water temperature stresses; and previous land management practices. Variability over time (temporal variation) results from weather patterns and management practices.

In particular, lack of nutrients, water stress, or plant diseases may form spatial patterns that change from year to year. Relevant properties of soil productivity are soil texture, soil moisture, clay content, organic matter content, nutrient availability,

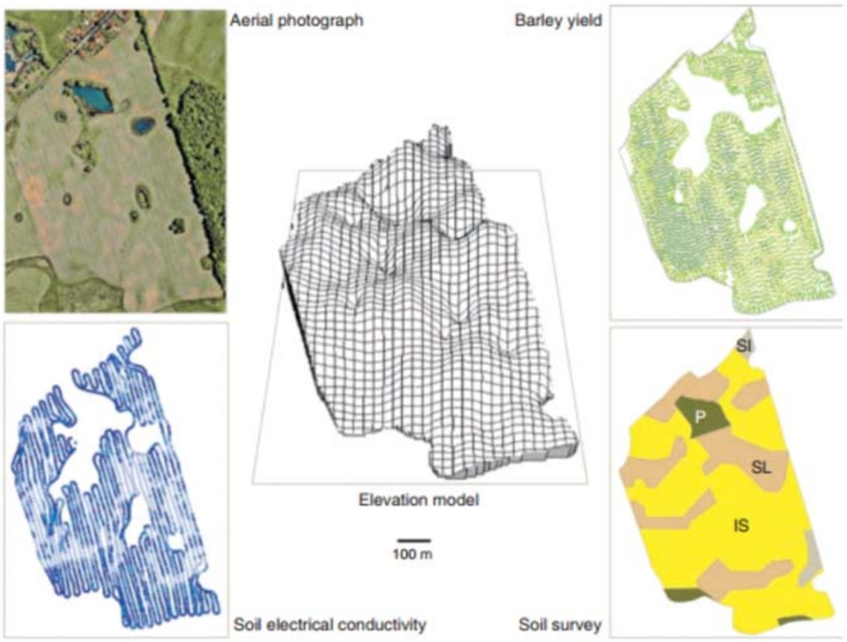

Fig. 11. Spatial variation across the field

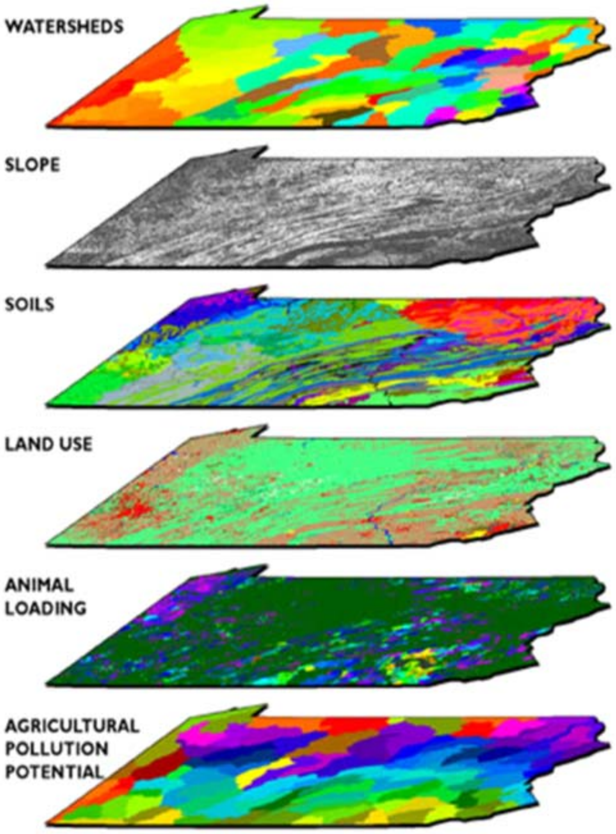

Fig. 12. The depiction of in field variability with RS, GIS and GPS technologies (https://www.ictworks.org/remote-sensing-agriculture/#.XZL7ckYzZ1s**)**

pH, and bulk density. Traditionally, these properties have been measured by soil sampling and offsite laboratory analysis or by on-the-spot measurement. Seasonally varying crop growth conditions such as water stress, lack of nutrients, diseases, weeds, and insects can be evaluated by visual inspection and laboratory analysis of plant tissue. The relatively coarse sampling/ measurement density of these conventional strategies may not be sufficient to reveal variation.

Soil and Crop Sensing

As conventional sampling and measurement are time-consuming, expensive, and may not be able to provide the desired spatial resolution, remote and proximal sensing technologies have been introduced to improve spatial resolution. These technologies can also improve the temporal resolution and hence offer the possibility of real-time management along with precision agriculture. Remote sensing acquires images via different sensors such as optical and radiometric sensors installed on an aerial platform or a satellite or drones, whereas proximal sensing systems are ground-based (mounted on a vehicle or carried by hand, moving platform) and linked to a GNSS receiver. The advantage of remote sensing is that images of the entire field can be captured in one snap over a large area, whereas proximal soil sensors can be moved over the desired area across the landscape to create high-density measurements that need to be mapped.

There is an enormous diversity of remote sensing data. The ground resolution, number and width of spectral bands, and timing of data collection differ among different service providers. Although remote sensing is useful for evaluating crop conditions, it provides a poor representation of the root zone environment, because the data represent the reflectance of the surface material, which might be bare topsoil, plant material, or a mixture of both. Proximal soil sensing allows for more direct detection of soil attributes than remote sensing. Three types of sensors are commercially available: electrical or electromagnetic sensors that measure electrical resistivity/conductivity or capacitance; optical sensors that obtain visible and near-infrared (Vis-NIR) spectra from within the soil; and electrochemical sensors that use ion-selective membranes to detect the activity of ions such as H^+, K^+, or NO_3^-. Soil compaction sensors for site-specific tillage will also be available in the near future.

Ultimately, the crop is the best indicator of variable growing conditions, and yield maps are most frequently used to evaluate crop performance. Yield maps summarize the overall impact of natural conditions, such as weather and soils, and of management activities. The observed spatial variation in quantity and quality of the harvest obtained by yield maps is directly related to the locally defined profitability. In intensive crop production, the input of water, N, and agrochemicals for plant protection is usually regulated during the growing season. Vis-NIR reflectance spectroscopy estimates plant biomass, chlorophyll content, and/or nitrogen stress. Detection and identification of weeds via machine vision systems are also feasible, whereas other crop status sensing techniques, such as laser fluorescence, thermal imaging, and ultrasonic proximity sensing, are still in the research stage.

Decision-Making

A typical cropping cycle that involves precision agriculture is shown in Fig. 13. Differentiated treatment of an agricultural field can be pursued using

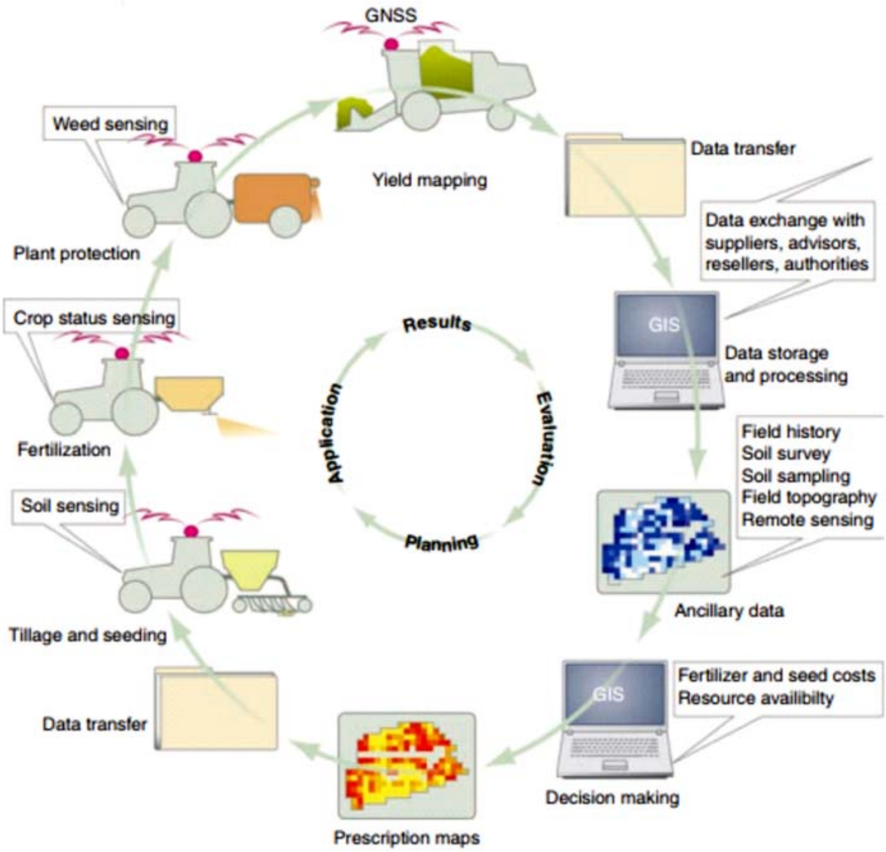

Fig. 13. Precision agriculture information flow in crop production

either a predictive or a reactive approach. In the predictive approach, information from yield history, thematic soil maps, field topography, and other spatial data records is used to predict variable crop performance and input needs. If a particular soil treatment can eliminate a yield-limiting factor that occurs in specific areas of the field (such as low soil pH or compaction), variable-rate technology can be used to solve the problem, atleast temporarily. If the yield-limiting factor is expensive or impossible to remove (such as poor water-holding capacity in a non-irrigated field), it makes sense to reduce the quantity of inputs applied because they will never be consumed by the crop and will most likely be wasted in the environment.

Precise Application, Guidance and Automation

Implements for site-specific management are available for most tasks, including tillage, sowing, mechanical weeding, and the application of fertilizers and other agrochemicals (Fig. 13). To date, GNSS-based vehicle guidance has been the most widely used precision agriculture technology. It allows the operation of agricultural vehicles along parallel tracks or on predefined paths, which results in less stressful driving, along with significantly fewer gaps and overlaps. Originally, navigation aids were used to assist operators in steering agricultural vehicles using visual feedback such as light bars or graphical displays. Recent auto-guidance systems steer agricultural vehicles without direct input from operators. Field robots (autonomous agricultural vehicles) are the next logical step in the automation of crop production. However, safety and liability are the main factors halting their adoption. It is currently unclear whether machinery will continue to grow in size and power or whether crews of smaller robots will conduct certain field operations in the future.

Decision Support System

Precision agriculture is the third stage of the agricultural revolution in which timely, precise inputs are applied at the desired location. It incorporated advanced technologies borne in the information age with a mature agricultural industry. It is an integrated crop management system approach that attempts to a different and precise amount of inputs as per the actual crop requirement for small areas within a farm field for optimizing the production considering the variability.

Precision agriculture uses advanced technologies like GPS, RS, GIS, variable rate technology (VRT), information and communication technology (ICT), and decision support system (DSS), which enhance productivity and efficient utilization of inputs to crop. The GPS was designed and is maintained by the US Department of Defence (DoD) as an accurate, all-weather navigation system. It is designed basically as a military system; now with some sort of restriction, it is available to civilians for positioning application. The GPS allows farmers to accurately navigate to specific locations in the field, year after year, to find a real-time location, collect soil samples or monitor crop conditions. A GIS is computer hardware and software that use feature attributes and location data to generate maps. It store layers of information crop scouting data, soil nutrient levels, yield maps, moisture level *etc*. Remote sensing along with GIS is highly beneficial for creating spatio-temporal basic informative layers and generating valuable integrated information by superimposing different basic layers. The VRT uses the GIS, GPS and remote sensing for real time application of chemical/fertilizer to crop at right place, at right amount and at right time.

DSS helps people make the decision based on the information that is collected (Fig. 14). It also takes information and solves problems. It provides data storage and retrieval but enhances the traditional information access and retrieval functions with support from model building and model-based reasoning. The DSS is used for assistance, management, and planning in many areas like agriculture. The information about crops can be turned into profitable decisions only when it is managed efficiently. Nowadays, data management is making smart farming grow exponentially as data have become the key element in modern agriculture to help producers with critical decision-making. The farm managed by DSS increases efficiency by avoiding the misuse of resources and the pollution of the environment.

Data plays a major role in DSS, so for the development of DSS for agriculture, collection of data is a must, including three broad groups: environmental data, crop/plant data and economic data. Environmental data are external variables affecting plant growth *e.g.* soil physical properties, soil nutrient status, water, temperature, climate, pests and diseases data. Crop/plant data include crop growth, crop yield, stress, chlorophyll content, plant dry weight, flowering time, and root biomass index. Economic data include seeding costs, harvest costs, grain prices, fertilizer, and pesticide application. Climate data such as temperature, relative humidity, solar radiation directly affect plant growth. Each crop requires a different level of temperature, relative humidity and solar radiation. The same crop at different crop growth stages requires a different level of temperature, relative humidity and solar radiation. Crop/plant data is important data for agricultural decision-making.

Agricultural Data Acquisition: Data acquisition in agriculture is mainly based on the following criteria:

a) **Location:** Field is the most direct and simplest method of collecting data using the GPS system for generating the graphs using RS and GIS. Both environmental data and plant data have been utilised to determine development stages.

b) **Method:** Manual, automatic, integration. Manual method is the simplest and direct method to collect data of plants which is time-consuming, tedious and chances of human error. Automatic methods have been developed to collect data in real time using sensors like.

c) **Tools:** There are various tools for collecting data in agriculture such as penetrometers, soil moisture probes, chlorophyll meters, tensiometer, near infrared sensors (NIR), hyper-spectral sensor, thermal sensor and normalized difference vegetation index (NDVI) meters.

d) **Distance:** It is categorized into three categories - ground level, aerial and satellite. Satellite imagery or remote sensing has been utilised to assess crop growth and yield variability for precision agriculture. Also sensors mounted on aircraft/ UAV are used for crop monitoring and mapping purpose.

ICAR GeoPortals

A geoportal is a web portal used to find and access geographic information (geospatial information) and associated geographic services (display, editing, analysis, *etc*.) via the Internet. Geoportals are important for effective use of GIS and a key element of spatial data infrastructure (SDI).

Geographic information providers, including government agencies and commercial sources, use geoportals to publish descriptions (geospatial metadata) of their geographic information. Geographic information consumers, professional or casual, use

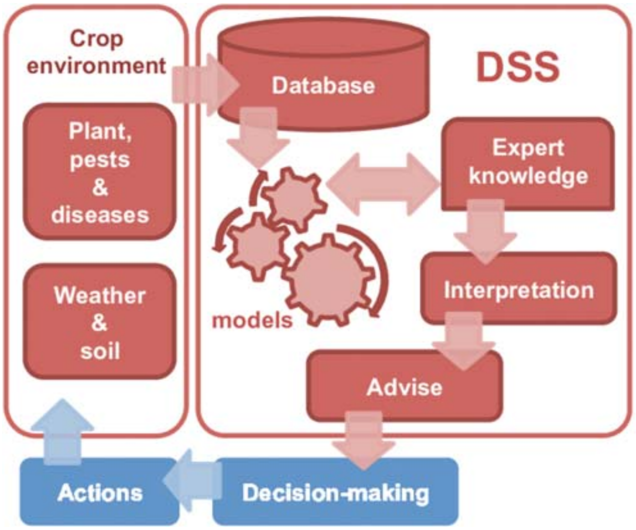

Fig. 14 . Block diagram of DSS
(*Source:* Creative Commons Attribution 4.0 International)

geoportals to search and access the information they need. Thus, geoportals serve an increasingly important role in sharing geographic information and can avoid duplicated efforts, inconsistencies, delays, confusion, and wasted resources.

Effective management of natural resources is a top priority in Indian agriculture. The ICAR GeoPortal is designed to equip the scientists to use the existing information on soil, water, climate *etc*., at different spatial levels coupled with real-time information on weather, crop status etc. to come out with new solutions. It aims to provide a digital platform in public domain:

- To facilitate the generation and compilation of data of agriculture having spatial context
- To store/host spatial database generated in NARS
- To provide visualization of spatial data as maps with contextual attributes
- To assimilate existing spatial agricultural data from other sources
- To provide tools for analysis of spatial data
- To allow spatial data access and sharing to clients across platform and GIS flavours
- Strengthen in-house technical capabilities

ICAR GeoPortal at present has the followings:

- An updated interface
- Two panels: Map View panel, Layer panel
- Geoportal Toolbar and Layer Toolbar
- Display of Layer Properties, Metadata and Layer Styles
- Selection of map scale
- Selection of base layers: OpenStreetMaps, (Bing, Google)
- Overlay of Map Layers: Order and Transparency
- Enhanced Query: Map extent and Map attributes
- Add WMS (Web Map Service) Layers from remote Geoservers
- Serve WMS layers to other GIS / Geoservers over internet

GeoPortal features

- Handles all type of spatial data Vector (point, line, polygon), Raster, Quadtree)
- Highly configurable due to open source technologies
- Extended functionalities
- Compatibility across platforms
- Provides web map services (WMS)
- Overlay state and district boundaries on any map
- Open source base layer till street level details
- Provision for users to upload their data directly to geoportal

The KRISHI Geo-portal provides several spatial layers collected by different ICAR research institutes at a centralized place for easy access to carry out such analysis, including around 100 layers from 15 themes. It has the applications like Meta Data Inventory for Spatial Data, Satellite Monitored India Crop Residue Burn Events, *etc*. The KRISHI Geo-portal provides basic visualization functionality by combining different layers which can be downloaded as images. It also provides downloading data for further analysis. The portal is expected to provide facilities to perform spatial-temporal analysis in the near future.

As per the growing demand in spatial data and spatial analysis, ICAR GeoPortal is going ahead with the re-engineering and rethinking of the wide collection of the geographical databases already existing in the ICAR geoportal particularly to the design and develop Geo applications for various agricultural domains.

Presently the ICAR GeoPortal has a spatial database, attribute database, and a meta-database which come together with the use of spatial operations and spatial analysis, the output in the form of maps along with their attribute information are obtained. The data types are either raster or vector.

There are suitability maps already available on the GeoPortal, procuring the basic data so that more maps can be generated using them on different themes, which will strengthen the geoportal. Providing intelligent solutions that deliver contextualized, location-specific, on-time, tailored and actionable information at each stage of the crop production cycle on which one can rely and profit will enhance the utility of the GeoPortal. The crop suitability profiling at various geographical levels is another feature envisioned to be available with the present GeoPortal.

Since spatial data plays a vital role in agriculture, the same has to be used to deliver agricultural extension and services as embedded services in the form of web-based geo-advisory services.

There are following methods in which Services of GeoPortal can be created and then they may be used for various purposed by the stakeholders:

- Viewing service = WMS (Web Map Service), WCS (Web Coverage Service)
- Discovery service = CSW (Catalogue Service Web)
- Download service = WFS (Web Feature Service)

The GeoPortal is being developed with the vision to cater the various spatial data and analytics need of ICAR, and for that, emerging technologies like Artificial intelligence (AI), Data Mining, Machine Learning needs to be integrated with it. Using Business Intelligence for extracting useful knowledge from the geodatabases will benefit the policy and decision-makers. Similarly, GeoAI or geographical AI, is a potential area to work in. Here, Artificial Intelligence is used in the area of Image Classification, Object Detection, Semantic Segmentation and Instance Segmentation in various agricultural domains. Along with AI, using Deep Learning for mapping is also planned to be used on the available spatial data.

The ICAR GeoPortal will also act as an integrated platform for agricultural sciences in the following ways:

- Reliable crop information is vital to the functioning of grain markets which could be used for informed decisions making on planting, Harvesting, and policy making. The platform can be used as crop monitoring and yield estimates.
- All information related to all ICAR Institutes on maps.
- GIS platform shall integrate soil and landscape data from various sources. Some of the key sources and classifications are:
    - o Agricultural Technology Application Research Institutes
    - o Krishi Vigyan Kendras
    - o Divisions and Units
        - ♦ Crop Science
        - ♦ Horticultural Science
        - ♦ Natural Resource Management
        - ♦ Agricultural Engineering
        - ♦ Animal Science
        - ♦ Fisheries Science
        - ♦ Agricultural Education and Extension

Case studies

Vineyards Precision Farming: To deal with three main issues of grape production *viz*., optimal water use, disease prediction, and controlled use of pesticides designed a precision agriculture framework in the Sula vineyards at Nashik, Maharashtra, India. The large-scale deployment at the Sula vineyards consists of wireless sensor nodes equipped with soil moisture, ambient temperature, relative humidity, and leaf wetness sensors. Based on the on-field sensor data, the ET and infection index were computed.

AgriSense: The distributed system comprises of wireless sensor nodes with environmental and soil-specific sensors – ambient temperature, relative humidity, leaf wetness, and soil moisture (Tripathy *et al.* 2013). The target mission was to predict the bud necrosis virus (BNV) disease of groundnut crops through a real-time DSS. The on-field deployment comprises five MICAz motes with a 25 m communication range, transmitting at an interval of 15 min. These nodes communicate among themselves using the ZigBee (IEEE 802.15.4) protocol at the 518 2.4 GHz RF ISM band. One gateway node sends the collected data to a remote server using GPRS communication. The remote server converts the raw sensor data to a usable format and saves it in its database for displaying through the graphical user interface (GUI). Based on the data of soil and environmental parameters, various data mining models such as Expectation Maximization (EM) and Gaussian Naive Bayes (NB) classifier were used to predict the pest/disease dynamics.

Conclusions

Soil proximal sensing technologies are needed to quantify the soil nutrient status rapidly on a spatial scale for efficient SSNM, higher nutrient use efficiency, and wise allocation of farm resources more efficiently. Implementing these precision nutrient management programs using sensor technologies will improve crop productivity and profitability and promote environmental stewardship under changed climatic scenarios. Rapid and non-destructive quantification of spatially-variable soil nutrients could be made possible using on-the-go sensors consisting mainly of optical, electromagnetic, and electrochemical sensors. Sensors developed for the on-the-go measurement of soil properties have the potential to provide benefits from the increased density of measurements at a relatively low cost. Conventional laboratory methods may offer highly accurate soil analysis. In situ based on on-the-go or hand-held soil nutrient sensors that offer real-time feedback are needed to improve farming efficiency and manage the environment. Proximal sensing instruments such as micro-electro-mechanical structures (MEMSs), thin-film filters, lasers, light-emitting diodes (LED), fibre optic assemblies, and high-performance detectors arrays based miniaturized hand-held vis-IR reflectance spectrometers, x-ray florescent spectroscopes are being used in precision agriculture for real-time crop performance and soil health monitoring. Besides the soil sensors, crop reflectance-based diffused reflectance sensors provide an accurate and spatially intensive method for diagnosing and applying the correct N rate in standing crops. These sensors allow real-time measurement of crop spectral properties with nearly immediate translation into N rate decisions, site-specific herbicide application for more efficient chemical weed management. However, there is an urgent need to develop cost-effective and rugged sensors for *in-situ* and sometimes on-the-go estimation of soil fertility and moisture retention status, crop growth monitoring, identification of nutrient deficiency in crops and efficient weed management.

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