National Symposium
on
Digital Farming: The Future of Indian Agriculture

ICAR-INDIAN INSTITUTE OF SOIL SCIENCE, BHOPAL
2-3 February 2023

Souvenir

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Organized by
Indian Society of Agrophysics
New Delhi

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Published in January 2023

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Dr. Pragati Pramanik Maity
Secretary
Indian Society of Agrophysics
Division of Agricultural Physics
Indian Agricultural Research Institute
New Delhi - 110012

Printed at
Mr. Print, C-126, First floor,
Naraina Industrial Area, Phase- I,
Naraina, Delhi-110028

डॉ. हिमांशु पाठक
सचिव (डेयर) एवं महानिदेशक (भाकृअनुप)

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GOVERNMENT OF INDIA
DEPARTMENT OF AGRICULTURAL RESEARCH & EDUCATION (DARE)
AND
INDIAN COUNCIL OF AGRICULTURAL RESEARCH (ICAR)
MINISTRY OF AGRICULTURE AND FARMERS WELFARE
KRISHI BHAVAN, NEW DELHI 110 001
Tel.: 23382629; 23386711 Fax: 91-11-23384773
E-mail: dg.icar@nic.in

MESSAGE

I am happy to learn that the Indian Society of Agrophysics (ISAP) and the Indian Council of Agricultural Research (ICAR) are organizing the National Symposium on "Digital Farming: The Future of Indian Agriculture" at ICAR-IISS, Bhopal on 2–3 February, 2023. The use of advanced technologies like remote sensing, GIS, robotics etc. has helped in efficient management and utilization of natural resources worldwide. The future challenges are even formidable to provide meaningful livelihood to millions while the demographic pressures are surging putting complex challenges before policy makers, scientists and the implementing agencies.

The agricultural production system is rather complex due to involvement of diverse players in its supply and value chain management. The development of a technology for improving the productivity and efficiency of a given production system is an output of the coordinated interplay of various disciplines of agricultural sciences. Agricultural Physicists have played a key role in developing smart technologies for enhancing productivity of the various crops and the systems in different agro-climatic conditions.

I hope that the deliberations on current and emerging issues of importance in digital agriculture such as robotics, drone technology, sensors, simulation modelling, biophysical techniques, remote sensing, machine learning and AI shall be held during the two day Symposium to emerge with viable research and management approaches for achieving food security and nutritional with greater natural resource use efficiency.

I wish the Symposium a great success.

(Himanshu Pathak)

27th January, 2023
New Delhi

भारतीय कृषि अनुसंधान परिषद
कक्ष क्र. 101, कृषि अनुसंधान भवन-II, नई दिल्ली-110 012, भारत
INDIAN COUNCIL OF AGRICULTURAL RESEARCH
Room No. 101, Krishi Anusandhan Bhavan-II, Pusa, New Delhi-110012, India

डॉ. सुरेश कुमार चौधरी
उप महानिदेशक (प्राकृतिक संसाधन प्रबंधन)
Dr. Suresh Kumar Chaudhari
Deputy Director General (Natural Resources Management)

27.01.2023

Message

I am happy to know that the National Symposium on "Digital Farming: The Future of Indian Agriculture" is being organized at ICAR-IISS, Bhopal. I am meticulously observing the vociferous progress made in the Indian agriculture since Independence. The advent of seeds and following green revolution would not have been that much remarkable without applying agrophysical practices under different agro-environments developed over the years by the devoted Agriculture Scientists. However, due to the current intensive agriculture demands more cautious and realistic approaches like robotics, drone technology, sensors, artificial intelligence are required to safeguard the environment and sustainable food production. Multi-pronged approaches including various components of modern day agriculture need to be evolved to tackle second generation problems of soils, water and environment. I firmly believe that the Indian agriculture has the strength and resilience to overcome such daunting challenges with the help of modern smart technologies like smart phone-based App, sensors, robotics, wireless sensors etc and achieve the goal of digital agriculture and the theme of the Symposium ""Digital Farming: The Future of Indian Agriculture" is apt and timely. The discussions and deliberations during the Symposium, I hope, would be highly useful and lead to solving the problems associated with agriculture, livelihood and global environmental security and will show a path towards digital agriculture.

I wish the Symposium a grand success.

(S.K. Chaudhari)

Ph.: +91-11-25848364 Fax: +91-11-25848366 Email: ddg.nrm@icar.gov.in Website: www.icar.org.in

भा.कृ.अ.प. – भारतीय कृषि अनुसंधान संस्थान, नई दिल्ली–110012 (भारत)
ICAR - INDIAN AGRICULTURAL RESEARCH INSTITUTE
(A DEEMED TO BE UNIVERSITY UNDER SECTION 3 OF UGC ACT, 1956)
NEW DELHI - 110012 (INDIA)

डॉ. अशोक कुमार सिंह, एफ.एन.ए., एफ.एन.ए.एस.सी., एफ.एन.ए.ए.एस.
निदेशक एवं कुलपति
Dr. Ashok Kumar Singh, FNA, FNASc, FNAAS
Director & Vice Chancellor

Phones : 011-2584 2367, 2584 3375
Fax : 011-2584 6420
E-mail : director@iari.res.in
Personal : aks_gene@yahoo.com
Website : www.iari.res.in

Message

I am indeed happy to learn that the Indian Society of Agrophysics and the Indian Council of Agricultural Research have taken the initiative to organize the National Symposium on "Digital Farming: The Future of Indian Agriculture" from February 2–3, 2023 at ICAR-IISS, Bhopal. I have been carefully watching the strident Agrophysics research made in the Indian agriculture. The advent of input response and dwarf high yielding varieties of wheat and rice with matching agrophysics research under different agro-environments developed over the years by the dedicated Agronomists led to the Green Revolution. However, the present-day intensive agriculture demands more cautious and pragmatic approach in order to ensure environmental safety and sustainable food production. In this context, use of agrophysics techniques like drone, remote sensing, simulation modelling, AI, machine learning etc. for developing digital agriculture is indeed an apt subject and relevant in the present context. It is expected that the participants of the Symposium drawn from different spheres of agricultural science will share their expertise and experience towards widening the horizons of knowledge in the proposed area. I congratulate the organizers for choosing a most appropriate theme of the Symposium. I am sure that the discussions and deliberations during the Seminar would be of great benefit to the scientific community in resolving the problems associated with agriculture, livelihood and digital agriculture.

I wish the Symposium a grand success.

(A.K. SINGH)

Contents

Future of Digital Agriculture in India

S.K. Chaudhari[1]*, Pragati Pramanik Maity[2] and Abhradip Sarkar[2]

[1]*Deputy Director General, ICAR, Krishi Anusandhan Bhawan-II, New Delhi-110012*

[2]*Indian Agricultural Research Institute, New Delhi-110012*

**Email: ddg.nrm@icar.gov.in*

ABSTRACT

Sustainable food security is the core concern of any civilization. Challenges become manifold with the increase in population and finite resource base. Cut-age technologies intertwined with digitalization is promising in almost all sphere of life including agriculture. Sincere efforts towards achieving the Sustainable Development Goals demands food security. Digital Agriculture has proved to be effective in various developed countries in increasing efficiency in the sector. Stakeholders' participation and enabling environment with government support is the key for success in Digital Agriculture practice in India. One of the ambitious planning of doubling the farmers income by Govt of India has recognized the strength of the Digital Agriculture. The article targets to explore present day Government initiatives and challenges in implementation of the Digital Agriculture in India.

Key words: Sustainability, Digital Agriculture, Artificial Intelligence

Introduction

Although global foodgrain production is catering to the needs at present time, but the issues in agriculture in changed environment needs to be managed more scientifically in collaboration with the cut-age technologies for meeting the future demands and aspirations. Food security is the pivotal for achieving the important Sustainable Development Goal 'To *eradicate extreme poverty and hunger*. For a sustainable inclusive growth, holistic agricultural growth is prerequisite. Agriculture is the main source is income throughout the world. The contribution of this sector is large for developing countries compared with the contribution in developed countries. Farmers are the driving force in this sector. It is irony that the farmers procure the inputs at retail price and deliver the produced at wholesale price. The consistent profit of farmers by and large remained a distant dream always compelling farmers in searching for more profitable ventures barring agriculture. The issues are more complex in case of developing nations crippled with diminishing resources and climate change. The future of the sector thus predominantly depends on shifting from the conventional practices towards practices intertwined with reforms, technology, mechanisation and digitalization in agriculture sector. Global agriculture is transforming from the conventional system to more and more technology driven agro-ecosystem with an eye for enhanced production coupled with optimization of profits and inputs towards achieving sustainable growth in changed climatic conditions. India being a large contributor (17%) of global agriculture and home for large chunk of malnourished people, should embrace the transformation with letter and spirit.

In India, the production of food grains is to the tune of 280 million Tonnes sufficient to catering to present day population. India ranks first in the production of milk, jute and pulses, and is placed second in producing wheat, rice, groundnut, vegetables, fruits, cotton and sugarcane. According to the Food and Agriculture Organization (FAO), India is the world's second-largest food producer (Lele and Goswami, 2017). It is also among the leading producers of fish, livestock, poultry, spices and plantation crops.

Although present day agriculture demand is being managed, meeting the projected demand in future with various constraints like marginal land holding, diminishing arable land, irrigation facilities, low yield, counter feit crop protection and population increase will not be work as usual. The shifting towards more technology driven practices is necessary. Multi-disciplinary efforts with stakeholders' participation would be the key. Acknowledging the present issues and future challenges of this sector, Govt of India has taken various initiatives of digital agriculture with a vision of doubling the agricultural income of farmers, the key for sustainable agriculture.

Digital Agriculture

With the technological advancement, digitalization in every sphere of life has become a key for future growth. Accumulation of data, modelling the same and proposing for possible solution to the given problem is the intending benefit of digitization. In Indian agriculture sector, the benefits of digitalization would be immense given the fact that 42% of the workforce is involved in the sector and the sector contributes 19% in Indian economy.

There are widely varied definitions of Digital Agriculture by experts in different context. Some of the associated vocabularies are precision farming, digital agro-ecosystem, smart farming, etc. In a nutshell all the definition encompasses a multidisciplinary approach using cut-age technologies, including artificial intelligence (AI), robotics, uncrewed aviation systems, sensors, and communication networks for informed decision by the stakeholders with optimum resources and enhanced profit associated with food security and sustainability. The system aspires for change/ modernisation in all parts of the food chain from farm to market.

Considering that the income of the marginal farmers, predominant in India, are not sufficient, Govt of India has taken the initiative of enhancing the farmers income in recent times. The Committee, constituted by Govt of India on Doubling Farmer's Income (DFI), in its report has appreciated the role of Digital Technology which can play a transformational role in modernizing and organizing how rural India performs its agricultural activities. (PIB dated 02.08.22)

One of ways of enhancing farmer incomes is through the use of Digital Technologies in Agriculture to increase the overall efficiency of the agricultural production processes as well as the entire value chain. "The future of food is unequivocally digital, and the future of digital is inevitably AI (Artificial Intelligence). From gene sequencing in seed production to Internet of Things (IoT) networks of implements and sensors that generate data and image recognition technologies that assay and grade crops and commodities, AI applications are being deployed across different aspects of agriculture." (Gurumurthy and Bharthur, 2019). India's National Strategy on AI also aims to realise the potential economic and social benefits the technology offers. Further, the National Strategy on AI recognizes agriculture as one of the priority sector areas for implementation of AI driven solutions (Niti Aayog, 2019).

Digital Agriculture Initiatives in India

Digital technologies are finding increasing use in the agricultural value system, and farmers are increasingly becoming more informed, as various measures are taken to provide them ready access to technology and information. (PIB dated 02.08.22)

Government of India has taken various initiatives to give a push to digital agriculture in the country, which are given below:

i. Government has finalized the core concept of India Digital Ecosystem of Agriculture (IDEA) framework which would lay down the architecture for the federated farmers' database. Further, the databases related to the schemes governed by the Department have been integrated. The IDEA would serve as a foundation to build innovative agri-focused solutions leveraging emerging technologies to contribute effectively in creating a better Ecosystem for Agriculture in India. This Ecosystem shall help the Government in effective planning towards increasing the income of farmers in particular and improving the efficiency of the agriculture sector as a whole.

ii. Under plan scheme viz. National e-Governance Plan in Agriculture (NeGP-A) wherein, funds are released to the State(s)/UT(s) for project involving use of modern technologies viz. Artificial Intelligence (AI), Machine Learning (ML), Robotics, Drones, Data Analytics, Block Chain etc.

iii. Sub Mission on Agricultural Mechanization (SMAM) is being implemented w.e.f April, 2014.The scheme aims at 'reaching the unreached' by bringing to the small and marginal farmers in the core and giving the benefits of farm mechanization, by Promoting 'Custom Hiring Centers', creating hubs for hi-tech & high value farm equipment, distribution of various agricultural equipment, creating awareness among stakeholders through demonstration and capacity building activities, and ensuring performance- testing and certification at designated testing centers located all over the country.

iv. National Agriculture Market (e-NAM) is a pan-India electronic trading portal which networks the existing Agricultural Produce Market Committee (APMC) mandis to create a unified national market for agricultural commodities. Digital services are provided to traders, farmers, Farmers Producer Organizations (FPO), Mandis through various modules of e-NAM platform such as FPO trading module, warehouse-based trading module.

v. Under PM KISAN Scheme, fund is directly transferred into the bank accounts of the eligible farmers under Direct Benefit Transfer mode. Farmers can do their self-registration through the Farmers Corner in the portal. PM-KISAN Mobile App was launched to broaden the reach of the scheme where farmers can view the status of their application, update or carry out corrections of name based on their Aadhaar card and also check history of credits to their bank accounts.

vi. Integrated Scheme for Agricultural Marketing schemes (AGMARKNET) to promote creation of agricultural marketing infrastructure by providing backend subsidy support to State, cooperative and private sector investments Services are provided through (AGMARKNET) portal which is a G2C e-governance portal that caters to the needs of various stakeholders such as farmers, industry, policy makers and academic institutions by providing agricultural marketing related information from a single window. It facilitates web- based information flow, of the daily arrivals and prices of commodities in the agricultural produce markets spread across the country.

vii. Agriculture Infrastructure Fund (AIF): To mobilize a medium - long term debt finances facility for investment in viable projects for post-harvest management Infrastructure and community farming assets through incentives and financial support in order to improve agriculture infrastructure in the country. Financial assistance is provided digitally in the form of Interest Subvention and Credit Guarantee for setting up post-harvest management Infrastructure to beneficiaries such as Farmers, Primary Agricultural Credit Societies (PACS), Farmer Producers Organisations (FPOs), Self Help Groups (SHG), State Agencies/APMCs.

viii. National Mission on Horticulture: It Promotes holistic development of Horticulture sector (including bamboo & coconut) HORTNET project is a web enabled work flow-based system for providing financial assistance under MIDH. It is a unique intervention to accomplish e-Governance in NHM where-in total transparency has been envisaged in all the processes of workflow i.e., online application filing, authentication, processing and online payment to the beneficiary's bank account through DBT.

ix. National Project on Soil Health and Fertility: To issue soil health cards to farmers of the country, so as to provide a basis to address nutrient deficiencies in fertilization practices. Soil Health Card Portal is available where farmers can track soil samples.

x. Development of Kisan Suvidha mobile application to facilitate dissemination of information to farmers on the critical parameters viz., Weather; Market Prices; Plant Protection; input Dealers (Seed, Pesticide, Fertilizer) Farm Machinery; Soil Health Card; Cold Storages & Godowns, Veterinary Centres and Diagnostic Labs. With market information, farmers are better informed about markets to sell produce, prevailing market prices and quantity demanded in the market. Thus, they can make informed decisions to sell produce at the right price and right time.

xi. The Indian Council of Agriculture Research (ICAR) has also compiled more than 100 mobile apps developed by ICAR, State Agricultural Universities and Krishi Vigyan Kendras and uploaded on its website. These mobile apps developed in the areas of crops, horticulture, veterinary, dairy, poultry, fisheries, natural resources management and integrated subjects, offer valuable information to the farmers, including package of practices, market prices of various commodities, weather related information, advisory services, etc.

xii. Government is providing advisories services on various crop related matter to the registered farmers through SMSs.

Future of Digital Agriculture in India

(i) According to Emerj AI Research, Artificial Intelligence (AI) is steadily emerging as part of the technological evolution in agriculture. This can be categorized into 3 main groups

- Agricultural Robots – to replace human labor-intensive tasks by robots
- Crop and Soil Monitoring – leverage computer vision and deep-learning algorithms to monitor crop and soil health.
- Predictive Analytics – develop and use machine learning models to track and predict various environmental impacts on crop yield such as weather changes.

(ii) Digital technologies can improve agricultural product traceability. This will provide the consumers with peace of mind about what they are consuming and also increase the value of farmers and their products.

(iii) Robosoft provides effective IT solutions for commodity traders, allowing them to increase the efficiency of their businesses. You can successfully build a complex supply chain and expand your business with our assistance. Robosoft aims to provide the farmers and the consumers with the most of the benefits of digital agriculture (Veeranjaneyulu, 2014)

(iv) Robo-commodity is a global leader in digital commodity management solutions that are powered by the cloud, blockchain, machine learning, and analytics.

(v) Prakasa Rao et al. (2021) have recommended numerous steps to develop digital ecosystem in Indian agriculture. These consist of:

1. Public organizations should provide data bases, conduct basic work on dynamical models of agroecosystems, data analytics platforms, algorithms for agronomic applications, conduct research on a 'feedback' loop with industry and farmers. 'Good Data' in place of 'Big Data' will hold promise in digital agriculture.
2. Industry should develop revenue models to create service platforms based on Big Data analytics and AI and reach individual farmers and closely work with agronomists for real-time farm advisories, create constant updates based on dynamical agronomy and create agri-value chains.
3. Collaboration among agricultural scientists, IT professionals, computer specialists and social scientists.
4. Protection of data privacy, compensations for data sharing by farmers, choice for famers to seamlessly change service providers; much like changing mobile service providers.
5. A data regulatory authority to address disputes. 6. Government should facilitate by way of IT infrastructure in rural areas, incentives to industry and farmers for smooth shift to digital ecosystem.

(vi) According to the NITI Ayog research on artificial intelligence, agriculture must expand at a rate of 4 per cent or higher right now to maintain an annual growth rate of 8–10 per cent. Digitisation is crucial for achieving this level of success. The NITI Aayog predicted in a report that by 2025, AI in agriculture would be worth $ 2.6 Bn and rise at a pace of 22.5 per cent Compound Annual Growth Rate (CAGR).

Challenges of Digital Agriculture in India

(i) High capital cost

The digital technologies are not yet pocket friendly for the marginal farmers as they are the majority in Indian scenario. Cost friendly alternatives and government subsidies may be explored to address the issues.

(ii) Modest land holding

In India average land holding of the farmers is marginally above 1 ha. Therefore mechanisation may not be applicable to a large extent. Land pooling by the farmers group in nearing areas may be explored so that the technologies can be fruitfully used.

(iii) Rental/ sharing practices

Average annual income of Indian farmers is quite less compared with the income of developed nation farmers. Therefore, cost intensive equipment may not be option for all farmers. Instead, the sharing or rental basis availability of the equipment's to the farmers may be explored.

(iv) Illiteracy in rural Areas

The technology base instruments and gadgets may not be user friendly to the marginal farmers who are mostly not technology literate. The aspects needs institutional support to the farmers to enhance their technology literacy.

Conclusion

Governments call for enhanced farmers income within a realistic time frame and its sincere efforts towards achieving SDG's, demands for a holistic digital ecosystem approach be adopted in agriculture sector. The approach is essentially multidisciplinary in nature. Extension of support of several ministries/departments along with the private participation including judicious workforce migration management is the key for efficient implementation. The idea of improving farmers profit with better management practices is not new. Implementation of digital ecosystem agriculture is entwined with the use of modern cut-age technologies and internet use. The proliferation of internet use base in the remote areas is the silver lining in implementation of the system in India. Although many a issues/challenges need to be addressed with the community support, corporate involvement, scientific intervention and government support for actually reaping the fruit, the adoption and results in the advanced countries is encouraging. Initiatives have already taken place at various levels. To ensure food security and sustainability with limited resources and changing climatic conditions, digital agro-ecosystem is a potential option not only for improving agriculture efficiency but also for inclusive sustaibale growth economy for a diverse country like India.

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Press Information Bureau (PIB), Posted On: 02 AUG 2022 6:03PM

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National Symposium on Digital Farming: The Future of Indian Agriculture
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Digital Tools for Organic Farming

Y.S. Shivay

Division of Agronomy, ICAR-Indian Agricultural Research Institute, New Delhi-110012

The current global population of 7.8 billion is projected to reach over 9 billion by 2050 (Grafton *et al*., 2015). To feed them, present food output must be increased by up to 98%. This is not the only issue; however, as we observe increasingly unpredictable rainfall patterns and more frequent floods and droughts, climate change poses a growing threat to weather-dependent agriculture. Additionally, 25% of the global greenhouse gas emissions are a result of the way we produce food now, which exacerbates climate change. Agriculture also has a big impact on the environment since it uses up a lot of vital resources like fresh water, which is quickly running out. Furthermore, we cannot expand the amount of land used for agriculture without further destruction. About 30–34% of the world's food is produced by 84% of farmers who are smallholders. Yet they face difficulties including low productivity, poor efficiency, and the aforementioned effects of climate change. To end world poverty, these industries must become more productive and profitable. Agriculture must become more sustainable in terms of its impact on the environment, the economy, and society by utilizing technology, digitization, and innovation.

Presently, conventional/chemical farming is facing a number of challenges, particularly those being thrust upon by climate change. Concerns have been raised about the lower input use efficiency in agriculture, which has led to higher production costs and negative environmental repercussions. A number of reports that are readily available also highlight the deterioration in food safety and quality, which may eventually have an impact on people's health. For survival on earth, everyone wants access to clean water, fresh air, and wholesome food. However, it's possible that the current agricultural production techniques won't be able to provide enough safer food without endangering the health of the land, plants, and environment. A move toward organic farming, especially in smallholder/marginal farm situations, could lead the way toward the production of high-quality food in such a context. In addition to enhancing the health of the land, plants, animals, and people, organic farming also contributes to a healthier ecosystem. Additionally, it boosts the revenue of the farmers by requiring less investment in the procurement of outside inputs. The Indian government and numerous state governments have stepped forward to support and promote organic farming in the nation after realizing its benefits and sustainability.

Current status

Currently, organic farming is being done by 3.4 million farmers on 74.9 million hectares of land in about 190 countries of the world (the year 2020). In India, organic farming had a total certified area of 4.34 million hectares under organic farming in the years 2020–21. Out of the total certified area, 1.68 million hectares were under cultivation and 2.66 million hectares were being harvested for the wild in 2020–21. The figures in Table 1 clearly show that the area used for wild harvest is decreasing while the area used for cultivation is growing, with 3.47 million tonnes of organic goods expected to be generated in the years 2020–21. The primary states embracing organic farming are

Table 1. Data on organic farming in India

Year	2016-17	2017-18	2018-19	2019-20	2020-21
Total production (million tonnes)	1.18	1.70	2.64	2.75	3.47
The total quantity of export (× 1,000 tonnes)	310	458	614	639	888
Value of total export (million US Dollars)	370	515	757	689	1041
Total arable land under certification (million hectares)	1.45	1.78	1.94	2.30	2.66
Total wild harvest area under certification (million hectares)	3.00	1.78	1.49	1.37	1.68
Total arable and wild harvest land under certification (m ha)	4.45	3.56	3.43	3.67	4.34

(https://apeda.gov.in/apedawebsite/organic/Organic_Products.).

Madhya Pradesh, Himachal Pradesh, Rajasthan, Uttarakhand, Kerala, Karnataka, Assam, Sikkim, and other northeastern states. This includes value-added products made from them as well as soybeans, cotton, sugarcane, oilseeds, pulses, basmati rice, spices, tea, fruits, dried fruits, vegetables, and coffee. The export of organic resources out of the nation is likewise rapidly rising..

A brief history of organic farming in India

Before the initiation of the green revolution (the 1960s), all Indian Agriculture may be considered organic by default. Sir Albert Howard (1930s and 1940s) championed organic farming far earlier, both in India and abroad. Along with creating the Indore composting method, he also studied and eventually came to value Indian traditional farming methods above modern agriculture. Sir Robert McCarrison established the Institute of Nutrition in Coonoor, Tamil Nadu, in 1918. It was then moved to Hyderabad and changed its name to the National Institute of Nutrition in 1969. Sir Robert McCarrison conducted a number of research on Indian cuisine and found that the growing usage of mineral nitrogen fertilizers had a negative impact on food quality. The majority of India's lands were transformed to chemical/modern farming during and after the green revolution. The Government of India and various State Governments took a number of actions to assist organic farming in modern times after realizing the necessity for an alternate form of agriculture.

Important initiatives

The movement for organic farming in the nation has recently received highly active support from the Indian government and various state governments. It has enhanced the current centres while also opening new ones for research and development. The government has also introduced a number of new initiatives to promote organic farming and provide farmers with the most recent advancements in this sector.

- The first major step taken by the Government was the implementation of the National Programme for Organic Production (NPOP) in the year 2001. The NPOP involved the accreditation programme for certification agencies, norms for organic production, and promotion of organic farming in the country.
- Another big step taken in 2004, the Indian government established the National Centre of Organic Farming (NCOF) in Ghaziabad, Uttar Pradesh. The National Project on Organic Farming (NPOF) has been implemented by this centre in Ghaziabad and its eight regional centres in Bangalore, Bhubaneshwar, Panchkula, Ghaziabad, Imphal, Jabalpur, Nagpur, and Patna.

The Participatory Guarantee System (PGS), a form of a free certification scheme for organic farming that is particularly suitable for the home market, is also implemented by the NCOF. A website has also been launched for the PGS certification system's online functioning; it can be viewed at www.pgsindia-ncof.gov.in. The National Centre for Organic and Natural Farming is the new name for this facility.

- A number of schemes have been launched by the Government that directly or indirectly support and promote organic farming in the country.
- The National Organic Farming Research Institute (ICAR-NOFRI) was established by the Indian Council of Agricultural Research (ICAR) in Gangtok (Sikkim) in 2016. This Institute's main goal is to conduct fundamental, strategic, and flexible research on effective organic farming systems that are economically feasible and environmentally sustainable in order to increase output, optimize resource use, and create higher-quality food.
- The Hon. Prime Minister of India, Shri Narendra Modi, designated Sikkim as an organic state on January 18, 2016, which was a significant breakthrough in the field of organic farming. Since that time, the majority of the northeastern states are eager to support organic farming in a manner similar to Sikkim had done.
- Growing organic crops using scientific methods is also vital to boost their profitability. The ICAR's Network Project on Organic Farming in Modipuram (Uttar Pradesh), which is working in this direction, is actively developing technology packages for the cultivation of organic crops suitable for different regions of the nation. Other than this, a number of ICAR Institutes and State Agricultural Universities (SAUs) are advancing organic farming through their research and extension initiatives.
- For the benefit of farmers and other stakeholders, the CSK Himachal Pradesh Agricultural University, Palampur, established a new "Department of Organic Agriculture" in 2009 to carry out research, teaching, and extension operations in organic farming.
- Additionally, the Punjab Agricultural University established a new "School of Organic Agriculture" under the "College of Agriculture" in 2017 to conduct multidisciplinary research, training, and extension activities for the advancement and dissemination of scientific knowledge on organic and integrated agriculture.
- A number of government colleges, universities, and other institutions provide training, certification, and degrees in organic farming.

Digital tools used in organic farming

The Union Minister of Agriculture and Farmers Welfare, Narendra Singh Tomar, announced the commencement of the Digital Agriculture Mission 2021–2025 in September 2021. To improve digital agriculture, five Memorandums of Understanding (MoUs) with Cisco, Ninjacart, Jio Platforms Limited, ITC Limited, and National Commodity and Derivatives Exchange (NCDEX) e-markets Limited were signed (NeML). With the help of cutting-edge technologies like AI, blockchain, remote sensing, robots, and drones, the Digital Agriculture Mission 2021–2025 hopes to promote and expedite projects in this area. The term "digital agriculture", also referred to as "smart farming" or "e-agriculture", refers to tools used in agriculture and farming to gather, store, analyze, and distribute electronic data and/or information digitally. The main digital instruments employed in organic farming and agriculture are:

1. Artificial Intelligence (AI)

2. Machine learning (ML)
3. Robotics
4. Drones
5. Data analytics
6. Blockchain, etc.

Artificial Intelligence (AI): AI systems help in organic farming to improve the overall harvest quality and accuracy – known as precision agriculture. The use of AI in agriculture makes it easier to find pests, diseased plants, and undernourished animals. Artificial intelligence (AI) sensors can identify and target weeds, then determine which technique should be used in that area.

Machine Learning (ML)

In order to increase the productivity and effectiveness of organic farming, machine learning has already started to play a significant role. For more effective agricultural output, precision agriculture depends on the collection, processing, and analysis of data (Javaid *et al.*, 2022). Utilizing cutting-edge technology, you can gather data on a modern organic farm using methods like:

1) Autonomous Vehicles
2) Variable Rate Technology
3) GPS-Based Soil Sampling
4) Automated Hardware
5) Telematics
6) Software
7) Sensors
8) Cameras
9) Robots
10) Drones
11) GPS Guidance, and
12) Control Systems

The farming system has undoubtedly reached a new level of efficiency owing to machinery based on machine learning. With the use of this technology, crop productivity has grown along with real-time tracking, harvesting, processing, and marketing.

Robotics

Through its integrated sensor system, the robot automatically navigates to inspect crops and gather information from the agricultural region. The robot efficiently completes bi-manual harvesting tasks with the dexterity demanded by the surroundings. Practitioners of organic farming may find this technique useful, particularly in affluent nations where a severe labour shortage exists.

Drones

Drones are uncrewed aerial vehicles (also known as UAVs), which are used for surveillance in various facets of life. Up until recently, the military, amateurs, and businesses engaged in the mining and construction industries were the main users of drones. But now that drone technology is more widely accessible, it can be used in a variety of agricultural fields, including organic farming. Although the technology is still in its infancy in India, numerous businesses are working to make it widely accessible to Indian farmers and prepared for use to boost agricultural production efficiency, particularly organic farming. Drone surveys used in organic farming can identify irrigation issues and improve water usage. The drone survey can be used by farmers to understand more about the soil characteristics of their property. Data from multispectral sensors can be utilized for organic nutrient management, field soil analysis, irrigation, and seed planting strategies.

Data Analytics

Every stage of the organic farming/agriculture lifecycle is being optimized to be more economical and efficient through the use of data analysis. Every step of the value chain, including crop selection, cultivation technique, harvesting, and supply chain management, is affected. The pattern of data that is readily available in the public domain, along with their better interpretation, can even be used to estimate the demand and supply of organic products.

Blockchain

Blockchain technology has the ability to track a variety of information about plants, including seed quality, crop development, and even the path a plant takes after leaving the farm. This information can increase supply chain openness and dispel worries about shady business practices. A successful and sustained organic food industry depends on transparency and trust. Supply chain data might be connected and protected from manipulation with blockchain technology with the aid of apps like Origin Trail important. The long-term sustainability of organic farming practitioners and their other stakeholders, such as customers, depends on this technology. Crop failure results in the loss of a lot of organic produce, but digitization can help.

Organic produce is now interspersed with computer and cloud-controlled technologies, making it more efficient, lowering uncertainty and reliance on speculative data, and boosting productivity and profitability. Organic farming organizations of all sizes can employ digital technologies. It streamlines on-training, conversion plans, farm activities, harvest planning, quality control, packaging, sales, documentation, and finance, which helps the company regulate the supply and demand of organic products on the market and generates larger profit margins. Dashboards for farm analytics provide intelligent data insights that let users make wise decisions at the right moment. Depending on the specific needs of the farm/FPO, the digital platform can be modified or combined with older financial software or smart hardware devices.

According to the NITI Ayog research on artificial intelligence, agriculture must expand at a rate of 4% or higher right now to maintain an annual growth rate of 8–10%. In order to achieve this degree of success, digitization is essential. According to a report from the NITI Aayog, AI in agriculture would be worth $2.6 billion by 2025 and grow at a rate of 22.5% compound annual

growth rate (CAGR). Currently, AI aids farmers in choosing better crops, hybrid seeds, and resource-efficient agricultural practices, which helps them enhance yield. It is also used to increase farming precision and productivity to help farmers build seasonal forecasting models.

Benefits of Digital Agriculture

By putting these technology solutions into practice, farms may be managed and monitored effectively. Farmers can act appropriately and avoid using excessive amounts of pesticides, fertilizers, and water since they have access to a complete computerized study of their crops in real time. Other advantages include: - Increasing agriculture productivity and lowering production costs; reducing the usage of chemicals in crop production; encouraging effective and efficient use of water resources; and improving the socioeconomic standing of farmers.

Applications of digitization software for organic farming

1) Supports multiple crops, locations, and users
2) Covers the entire 'Farm to Fork' cycle
3) Farmer group management
4) Labour and inputs optimization
5) Yield estimation and harvest planning
6) Geo-mapping and smart crop advisory solutions
7) Production and sales planning
8) Farm analytics for data-driven decisions
9) Organizational hierarchy mapping
10) Can be accessed over the web, mobile, or tablet

Traceability is the major and most significant issue being addressed with the use of technology and digitization. For many value chains, traceability provides complete visibility of the produce from the farm to the buyer. Buyers can follow the footprint of the food to the farmer groups that cultivated it thanks to traceability solutions based on QR codes or scanning tags. This is especially useful for younger consumer age, who are aware of the problems related to cultivation. In this application, information is sourced utilizing mobile devices or dynamic technologies, such as the web. Produce supply chains can be managed using digital technology, which continually adds transparency to the chain as a whole. All farm and farmer activities as well as record acquisition exchanges can be digitalized using the framework. Additionally, farmers get paid on time and fairly as a result of this. Market linkage is another application of digital technology that connects farmers/growers and consumers via a gateway. By giving the buyer exposure, encourages growers and farmers to be interested in global commercial sectors. It informs farmers on the costs and prospects of the present market, facilitating effective negotiations. Modern agriculture technology has a place in financial services as well because it can assist with managing all aspects of farming's budgetary administrations, from credit and installments to crop insurance and collections. It offers accuracy and transparency with a platform that can be integrated with budgetary institutions. Additionally, digitization aids in farm management. Farm management involves digitizing farm information and farmer profiles. Digital technology can also be useful in the disciplines of Geo-tagging, Geo-referencing, and biometric data.

Some challenges standing in the way of digital agriculture

- Large, indexed, and standardized data sets, which are now in short supply, are needed by machine learning algorithms.
- Early pest identification requires connectivity, machinery for precision farming, and sensors, none of which are practical for most Indian farmers.
- Farmers' privacy concerns and restrictions on who can access personal data need to be addressed.

The biggest opportunity for Digital Agriculture across the entire agriculture value chain from the upstream (inputs and production processes) to the downstream (post-harvest and value addition including food processing) is with the emergence of FPOs in India. These FPOs serve as a platform for combining farmers' production and selling of their produce. A win-win situation for all parties involved is created at the same time when technology becomes broadly accessible and reasonably priced through the FPO for even the tiniest of farmers.

Conclusion

The declining response to farm inputs in conventional farming has compelled growers/farmers and other stakeholders to look for alternative methods of farming/agriculture. India is on the right path to transforming its agricultural sector and providing accelerated value to all farmers. Organic farming is supposed to partly fill this gap and enhance sustainability in the areas of adoption, environment, and farmers' economy. Further, the use of digital tools in organic farming will avoid wastage and enhance the efficiency of inputs, increase productivity, environmental sustainability, social well-being and overall improved human health.

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National Symposium on Digital Farming: The Future of Indian Agriculture
2-3 February 2023, ICAR-IISS, Bhopal

Status and Scope of Policy Interventions in Digital Agriculture in India

Ch Srinivasa Rao, P.D. Sreekanth and G.R.K. Murthy

ICAR-National Academy of Agricultural Research Management, Hyderabad

Agriculture sector is the mainstay of the Indian economy, it contributes about 20.2 percent gross domestic product (GDP) increasing from 19.9 percent recorded in 2020-21, and more importantly, about half of India's population is significantly dependent on agriculture and allied activities for their livelihood. The contribution of agricultural sector to GDP has continued to decline over the years, while that of other sectors, particularly services, and has increased. Food grain production in the country is estimated to be a record 308.65 million tonnes, which is 11.15 million tonnes higher than 2019-20 but in other side small and marginal holdings account for 85% of the total operational holdings farming 157.35 million ha or 44% of the total operated area. The average size of holdings for all operational classes (small, marginal, medium & large) has declined over the years i.e. down to 1.16 ha in 2010-11 from 2.82 ha in 1970-71. Farmers are still not able to earn proper earnings. Even after over seven decades of planning since the independence, majority of the farmers are still facing problems of poor production and poor returns. According to Indian Council for Agricultural Research (ICAR) the demand for food grain would increase to 345 million tonnes by 2030. The rapidly Increasing population, average income and globalisation effects in India will increase demand for quantity, quality and nutritious food. Thus, pressure on decreasing available cultivable land to produce more quantity, and quality of food will keep on increasing.

This is possible with the help of digital precision agriculture technology. From drones to satellite images with sensors along with digital education technology, the agricultural industry is changing in a remarkable way. Modernization of agriculture and the use of digital technology have resulted new concepts to emerge such as digital agriculture with the help of digital education. Digital Agriculture is Information and Communication Technologies (ICT) and data ecosystems to support the development and delivery of timely, targeted information and services to make farming profitable and sustainable while delivering safe nutritious and affordable food for all.

Initiatives under Digital Agriculture in India

Recently the government has launched the Digital Agriculture Mission 2021–2025. The purpose of the mission is to support and accelerate initiatives based on new technologies, including artificial intelligence (AI), block chain, remote sensing, and geographical information system (GIS) technology, and the utilization of robots and drones in agriculture practices. In this initiative, the government has signed five memo understandings (MoUs) with ITC Limited, Ninjacart, CISCO, Jio Platforms Limited, and NCDEX e-markets Limited (NeML) to take forward digital agriculture through pilot projects. This project is under a digital mission now operating on a pilot basis in a different state to accelerate and support projects based on new technologies.

Future Digital Agriculture in India

Technological involvements such as remote sensing, soil sensors, drone or aerial surveying, and market insights permit farmers to gather, visualize and assess crop and soil health status at different stages of production, and water management in a convenient and cost-effective approach. Such technology gives an initial indicator to identify probable challenges and offer options to deal with them promptly. Traditional farming requires more labour to monitor the crop and needs physical equipment, time, and effort. However, the innovation of new technology, such as internet of things (IoT), and machine learning devices, once can collect data and deliver exact information through mobile apps. This technology also is used for different tasks such as soil status, temperature, and moisture detection, plant and animal tracking, and many more. Drones technology provides aerial imaging and plotting of near and wide-ranging landscapes. Drones are also utilized for livestock tracking and grazing monitoring using global positioning system (GPS) technology. This technology capture photos ranging from simple visible-light spectrum to multispectral imagery that helps in crop, soil, and field studies.

Artificial Intelligence/Machine Learning (AI/ML) algorithms provide exact information on their fields. Using analytics and big data, information on crop production, irrigation weather forecasts, and statistics of crop disease or anything related to agriculture transformed into useful information. With the help of block chain technology, we can do precise data about farm inventories, track food, and make quick and safe transactions. The benefit to the farmers doesn't have to depend on paperwork or files to record and store important data. Incurring labour costs and less labour is a significant issue for farmers. as a result; agricultural robots are being developed. Help farmers with various tasks such as fruit gathering, harvesting, planting, transplanting, spraying, seeding, and weeding (Soam *et al.*, 2018).

Challenges of Agri-technology in India

The challenges and strategies for technology adoption in India are that most farmers belong to Small and marginal land holdings with low income and most rural farmers are illiterate, this is the main barrier to farmers that holds them back from modern technology in agriculture practices. Many approaches have been taken by public and private ownership over ICT adaptability in farming. However, they have not get the desired result in terms of awareness and adaptation though they have proved helpful in improving yield, reducing cost, and fetching higher returns. The involution of technology depends on the education level of the people involved in an agricultural activity that will increase their ability to obtain, process, and use information relevant to different technology adoption. Such as for, precision farming requires some amount of capability in using software and hardware. Mainly technology like GPS, GIS, remote sensing (RS), sensors, etc. (Murthy *et al.*, 2019; Srinivasarao *et al.*, 2019)

Collecting information about machinery is another problem that determines adoption. Knowledge of the local technical expertise and assistance is another challenge for adopting Agri-technology in India. The latest mechanization and technology are expensive for the economic reach of Indian farmers (Sreekanth *et al.*, 2020). The latest technology farmers were cannot use due to high cost and maintenance and normally not even available. One of the biggest barriers to adopting modern agriculture is the need for more awareness and focused training in farming communities. Ancient farming techniques predominate in Indian agriculture, and the same agriculture practices and ways of cultivation are continuously done from generation. Confrontation and rigidity are two major hurdles in the adoption of the latest technology in agriculture.

Way to overcome the challenges in digital farming

With the swift developments taking place in Digital applications, there is a need to leverage and capitalise its potential in Agriculture in various contexts like Research leading to field applications and Education leading to quality, access and equitability for learners like students, farmers and other stakeholders.

This needs a concerted approach by evolving and laying various strategies, protocols, and roadmaps through carefully designed and guided policies. Policymaking needs a collective wisdom from various cross-sections of the stakeholders like researchers, policy makers, Technology developers, Administrators, Teaching faculty, Students and Farmers. Agriculture being a vast domain, any effort towards a stable and futuristic policy will ensure a stable progress in feeding the growing population. Thus it is important to revisit the existing policies and strategies and identify the grey areas where there is a need to make headway in policy making for leveraging Digital applications in Agriculture.

Status & Scope of Policy Interventions in Agricultural Education

Need for broad-based quality education has long been felt, as much as the requirement for improved livelihood opportunities. However, the efforts have been mostly localized, and have not been towards connecting those requirements together. While modern digital technologies have been leveraged in these contexts, a framework for scaling up to connect in line with national missions such as Digital India has largely been missing. There is a dire need to create a framework of quality education incorporating digital technologies that will organically facilitate improved livelihood and create economic opportunities, and potentially take us closer to *Atmanirbhar Bharat*.

Government Initiatives in Digital Learning

Digital / Online education has emerged as the most noteworthy alternative to conventional face-to-face classroom teaching. It allows teachers as well as learners to access the plethora of educational technologies. Online education in India has perceived an enhanced acceptance over a few years. The Government of India has taken several strategies to boost online education to cover all students at all levels of education and in all geographical locations, even in the remotest parts of the country. The initiatives such as *Swayam Prabha*, PM e-*Vidya*, and *Diksha* portal (e-*pathshala*) are facilitating learners to access e-learning content across the country.

The Indian government has also launched massive campaigns like '*Bharat Padhe Online*' and '*Vidya Daan 2.0*' for boosting e-learning and intensifying online education. Besides, Digital India and Skill India are among the several government initiatives that are providing impetus to the growth of online education in the country. Virtual labs is an initiative of the Ministry of Education to provide remote access to simulation-based Labs in various disciplines of Science and Engineering. Project OSCAR (Open Source Courseware Animations Repository) provides a repository of web-based interactive animations and simulations, referred to as learning objects (LOs). These learning objects cover topics in science and engineering at the college level, and maths and science at the school level.

Further, many state governments and Ed-Tech companies have also taken several programs to boost digital learning in their respective states. According to KPMG India and Google, the major drivers for online/blended education in India include phenomenal growth in Internet and smartphone penetration, low cost of online education, digital-friendly government policies and escalating demand by working professionals and job-seekers for continuing education (Bansal, 2017; Srinivas and Srinivasarao, 2020). With the active involvement of governments at all levels, digital education is expected to grow continuously in the future too.

The advances in technologies have brought a lot of innovation into the education field. One of those undoubtedly is Massive Open Online Courses (MOOCs) which are considered also to be the ultimate way for educational content delivery to the most distanced students. (Kastrati *et al.*, 2020; Murthy *et al.*, 2019). Massive Open Online Courses (MOOCs) are considered to be disruptive technological form of online education that is changing the educational landscape globally, as it enhances equity and access of education to under-privileged target groups. There is a need to understand the concept of MOOCs and evolve suitable strategies to internalize in Indian context. In the context of agricultural education in formal sector, Digital Learning has a greater role to support the NARES in many ways like

- Severe shortage of experienced faculty/domain specialists in universities
- Providing quality education in different modes (like ebook and beyond)
- Lack of Information Technology views to promote technology as a driver of education
- Reaching and educating the remote target groups like rural, hilly and remote areas
- Diverse target groups with varying literacy levels
- Development of entrepreneurship
- Providing employment-oriented education to the rural youth/entrepreneurs

Status of Existing Policies

There has been awareness at National level in identifying the potential, importance and the role of digital learning to bring in wide scale educational reforms. Policies emanated from National Educational Policy 2020 (NEP), University Grants Commission (UGC) and Broad Subject Matter Area (BSMA) point to the importance of digital learning in the current educational landscape.

National Education Policy (NEP)-2020 (Section 9.3) emphasizes increased access, equity, and inclusion through a range of measures, that includes Online education, and Open Distance Learning (ODL). Open and Distance Learning (ODL) will be expanded to aim at a Gross Enrolment Ratio of 50%. Measures such as online courses and digital repositories, funding for research, improved student services, credit-based recognition of MOOCs, etc., will be taken. A comprehensive set of recommendations for promoting online education is needed considering the recent rise in epidemics and pandemics in order to ensure preparedness with alternative modes of quality education whenever and wherever traditional and in-person modes of education are not possible. NEP 2020 also aims at providing infrastructure and learning materials accessible and available to learners with disabilities. An Academic Bank of Credits (ABC) shall be established which would digitally store the academic credits earned from various recognized Higher Education Institutes (HEIs) so that the degrees from an HEI can be awarded taking into account credits earned. University Grants Commission (UGC) recommends students could complete up to 40% of courses per semester through SWAYAM India's official MOOC platform. According to UGC Regulations 2018, Indian Universities can offer fully online degrees. Broad Subject Matter Area (BSMA) of ICAR recommends the Board of Studies (BoS) to identify online courses which can be offered by a host institute to all others. BSMA recommends a maximum of 20% online courses in a semester at PG level.

Scope of Policy interventions for digital learning in Agricultural Education

Policies and directives point to the organizational approach to develop, manage and operationalize digital education besides encouraging the learners to opt for online learning. There is a need to have comprehensive policy that imbibes the soul of NEP 20, UGC guidelines and our own BSMA to address the following broad areas

- **Digital content and course production** – This enables uniformity in content developed by individual institutes so that the same can be used across the educational organisations
- **Methodology or strategy to offer online courses** – It is very important to have a suitable mechanism to offer online courses with supporting IT infrastructure and software's like Learning Management System (LMS) and creation of task groups to implement them.
- **Evaluation and certification protocols** – One concern in online courses can be sound evaluation protocols (or the lack of) as there is scope for unethical practices to complete the courses. Sound protocols have to be designed to prevent such discrepancies.
- **Sustainability and revenue generation model** – Digital education can be considered to be a self-supporting model with an initial traction support. With suitable action/policy plans, it can be made as revenue generation model beyond sustainability also.

Summary and Conclusions

During this last few years, there has been spurt in innovations in farming and its education. While some are being guided and regulated by some policy guidelines, many areas still remain to be channelized through proper policy interventions. Agricultural education has a vast scope to leverage on the new technologies like digital agriculture and need to internalise the policies and experiences thereupon from other subject domains.

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Digital Technologies and Applications for Agricultural Transformation

Srikanth Rupavatharam, Mukund Patil, Pranuthi Gogumalla and M.L. Jat*

International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Hyderabad-502 324

**Email: mangilal.jat@icrisat.org*

ABSTRACT

Digital technologies and applications encompass smart farming using the Internet of Things (IoT), food sensing, data-driven decision support and extension systems, platforms for access to market and finance. Digital agriculture can enable farms to become more productive and profitable while also improving their ability to adapt to climate change. In this article, we review the existing digital agriculture technologies and their role in transforming current agricultural systems into a sustainable ecosystem. Research notes, conference papers, peer-reviewed articles, and business reports about digitization in the agri-food sector were explored using online data bases in Web of Science, Scopus, Research Gate, Google Scholar, and specialized websites and blogs. The behavior of farmers is expected to be impacted by digital technologies that enabled agriculture services, from inputs, social interactions, decision-making, bargaining power, and their relationships with other stakeholders in the agri-eco system. Digital technologies are steadily transforming agriculture into a data-driven, informed and structured industry that opens avenues to meet the challenges of climate and food crisis.

Key words: Agriculture4.0, Internet of Things, Drones, Crop phenotyping, Artificial Intelligence, Satellite remote sensing

1. Introduction

The science of Digital Agriculture (DA) has been gaining prominence with the advent of fast-paced progress in technologies which can impact both the development and last-mile delivery of agro-technologies and services to support smallholder farmers. Digital Agriculture offers a wide range of technology solutions for farmers including smart farming, food-sensing, precision agriculture, data-driven decision support and extension systems, channels for improved market access, and financial services (Townsend *et al.*, 2019). Digital Agriculture can contribute to increasing the productivity and profitability of farms and strengthening access to diverse marketing channels and building resilience to climate change. However, in most cases, Digital Agricultural technologies have not been adequately accessed by smallholder farmers, women, and youth (CTA, 2019). The United Nations Secretary General's strategy on the use of digital technologies for accelerating the achievement of Sustainable Development Goals (SDGs) identifies food security as a critical area which will be disrupted profoundly by advances in Digital Agriculture (United Nations, 2018).

In India, the agriculture sector, currently valued at US$ 370 billion, is one of the major pillars of the Indian economy. Therefore, technology-led transformation in agriculture is a priority agenda of the Indian government not only for the economy but also towards a quest to meet food and nutritional security in the face of challenges of climate change, unemployment, and sustainable livelihoods of smallholder farmers. Technology is critical to transforming agricultural development and digital agriculture is a potential game changer in boosting productivity and enhancing climate change resilience in Indian agriculture.

2. Methodology

The demand for digitization in Indian agriculture is well understood and acknowledged, likewise, efforts have been made towards digital transformation. The information on digital agricultural technologies available, their use cases, and applications pertaining to each technology were mainly reviewed from Google scholar and Google play store. Research notes, conference papers, peer-reviewed articles, and company reports about digitization in the agri-food sector were all included in the overview. Searches were conducted on other electronic databases and online sources such as Web of Science, Scopus, Research Gate, Google search engine, and specialized websites and blogs.

In total, more than 100 documents from the selected databases covering the topics like digital technologies for agriculture, agro-advisories, climate-smart farming, Internet of Things, block chain, carbon farming, MRV platforms, crop protection applications, high throughput crop phenotyping and remote sensing based agricultural applications. For a better understanding, we have grouped digital technology applications into three broad themes viz. Digital technologies for (i) last-mile delivery, (ii) accelerated crop improvement, and (iii) investments & policy as depicted in Figure 1 as described under section 3.

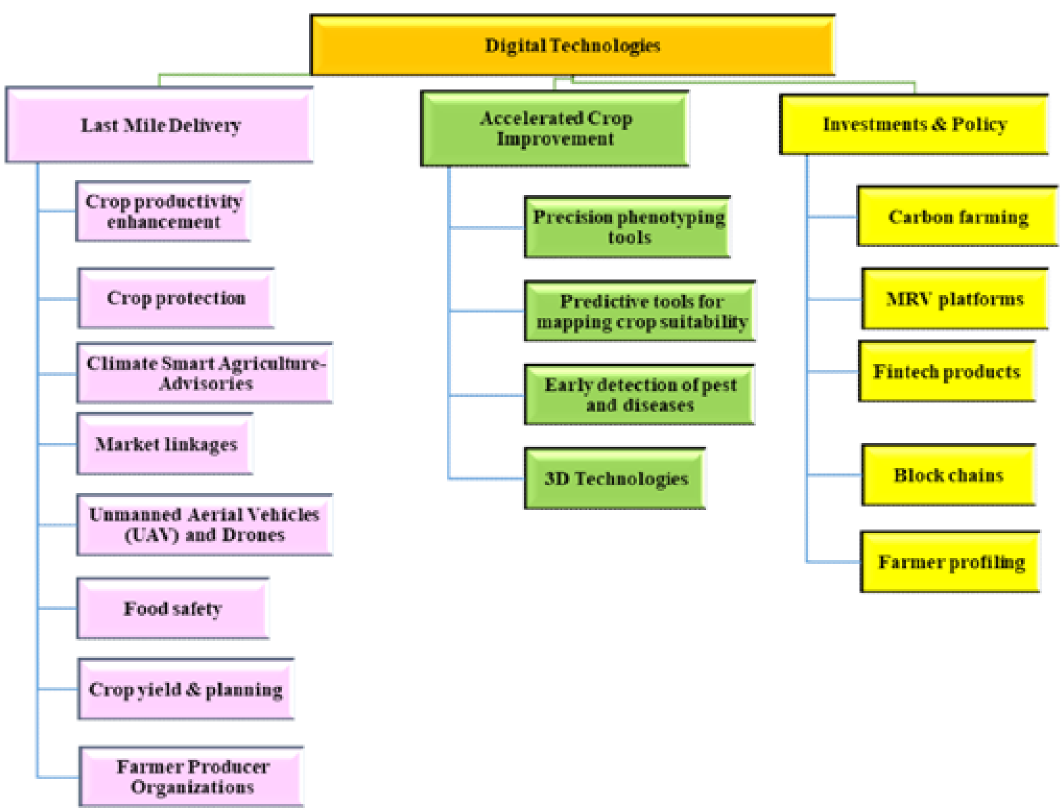

Figure 1. Classification of digital technology applications for agricultural transformation

3 Digital technologies for last-mile delivery

3.1 Crop productivity enhancement

For enhancing crop productivity, timely access to customized information on recommended crop varieties, fertilizer doses, pests and disease control measures, abiotic stresses, preventive and ameliorative measures, marketing strategies, etc. are critical. Many digital technology platforms provide crop-specific customized advisories on best practices. In 2021, the Union Minister of Agriculture & Farmers Welfare, Government of India announced the initiation of the Digital Agriculture Mission 2021–2025. There are several digital platforms but the popular digital platforms and applications are enlisted below:

'Agropedia' is an agricultural knowledge repository mimicking Wikipedia with universal and localised material for a range of users designed with multilingual interfaces (Kamani *et al.*, 2014). It is a one-stop hub for information on the agriculture ecosystem.

There are numerous smartphone applications, and a few popular ones include 'FarmRise', from Bayer, 'AgriCentral' from Olam that support smallholder farmers with daily agronomic guidance to increase productivity and incomes of farmers. This network of Indian farmers gets local information that can help them choose crop production strategies more wisely. Given that almost 70% of smallholders have access to cell phones, this pilot project could serve as a useful example for other parts of the world. The International Rice Research Institute and its collaborators developed a platform using the principle of site-specific nutrient management to identify the best nutrient management practices for individual rice fields in Odisha and Bihar states. International Plant Nutrition Institute (IPNI) together with International Maize and Wheat Improvement Center (CIMMYT), Indian Council of Agricultural Research (ICAR) and State Agricultural universities have developed Nutrient Expert Decision Support tool for precision nutrient applications

3.2 Crop protection

Pest identification and timely application of precise pest management information is crucial for Integrated Pest Management. In pest and disease control, image-based recognition has been proposed using Artificial Intelligence (AI) & Machine Learning (ML) techniques which aid in feature detection, candidate region formation, regional image categorization, and position refining.

There are few applications like Plantix, an android app from an Indo-German startup company having its base in Indore, India is the most popular agricultural app in the globe with more than 25 million users. Plantix uses AI based algorithms to detect pests, diseases and nutrient deficiencies (600) in more than 35 crops including cereals, pulses, vegetables and fruits with an accuracy of more than 90% (Rupavatharam *et al.*, 2020). It is a crop advisory app for farmers, extension workers, gardeners and experts.

'PlantVillage Nuru', a mobile app developed at Penn State University (USA) in close cooperation with subject matter experts at the CGIAR institutes to diagnose crop pests and diseases in the field without mobile connectivity. The app is the result of in-depth analysis comparing the precision of machine learning models to that of human specialists and extension workers (Mrisho *et al.*, 2020).

3.3 Climate Smart Agriculture- Advisories

Digital technologies that can contribute to improve decision-making based on weather and climate are in vogue because of variability and climate change. In order to detect potential changes to the climate system, such as flooding, droughts, heat waves, cyclones and tsunamis, wireless sensor networks, Geographical Information Systems (GIS), and ICTs have been used. Remote sensing technologies can be utilized for risk modelling, early warning, rainfall mapping, monitoring, and spatial planning in cyclone and flood-prone areas. Weather based advisories specific to crops and geo-locations are available to farmers.

India Meteorological Department's (IMD) 'Agromet' is a web-based platform that provides weather and climate based agro-advisories that are crop, district specific with a graphic user interface that allows user to easily access information (Gangopadhyay *et al.*, 2019). There are several other applications that incorporate weather-based advisories extended by IMD. Apps such as 'AgroStar Agri-Doctor', 'AgriApp', 'KVK Mobile App', 'BharatAgri', 'Fasal Salah Agriculture App', and 'Meghdoot' are available in google play store. 'Meghdoot' is a user-friendly mobile application that gives farmers crop advisories based on weather data. It is a joint effort of the Indian Council of Agricultural Research (ICAR), Indian Institute of Tropical Meteorology (IITM), and the IMD (Dhulipala *et al.*, 2021).

3.4 Market linkages

Farmers in rural areas are compelled to sell their commodities for lower prices to local middlemen because agricultural markets are decentralized and lack real-time market information. Farmers are unable to expand their operations and raise their income as a result of the information asymmetry. To solve this, many organizations have developed market access apps that can assist farmers in selling their produce at their discovered higher prices to ecosystem players.

India's National Agriculture Market, often known as 'eNAM', a Government of India initiative is an online marketplace for agricultural products. Farmers, merchants, and purchasers can trade commodities online thanks to the market. The marketplace aids in more accurate price determination and offers resources for efficient promotion of their goods (Kalamkar *et al.*, 2019).

Mobile app 'Agribuzz-AgriApp' provides market information to farmers and other stakeholders. It offers a platform where app connects and brings together the farming community and helps them in selling, buying, and exchanging agriculture commodities and services locally without middlemen through an advertisement or listing (Balkrishna *et al.*, 2021).

Ninja cart, De Haat, Big Haat, AgroStar are few other prominent digital applications available to farmers in market space for agri inputs like seeds, fertilizers, pesticides, herbicides, farm machinery, equipment etc.

3.5 IoTs for irrigation, nutrient and plant stress management

The Internet of Things (IoT) is a system of wirelessly connected things that can communicate data to a larger network without human involvement. IoT connectivity is quickly transforming agricultural field applications. Farmers can continuously track resources like water, nutrition requirements and plan strategic decisions by monitoring their farms.

A fully automated farm, 'GroTron', is an IoT enabled fertilization and irrigation management system. It makes use of a variety of meteorological, soil, and plant-based sensors, or IoTs, to identify crop problems and begin fertilization and irrigation. Arable Mark 2.0, CropX, Soil Sens GO, BT Soil Moisture Sensor, Soil NPK Sensor from teralytic.com, atechindia.com and jxctiot.com are few IoT sensors for irrigation and nutrient scheduling available in markets.

3.6 Unmanned Aerial Vehicles (UAV) and Drones for crop management

The use of drones in agriculture has the potential to significantly transform the current agriculture. This emerging technology can help reduce time and increase the efficiencies of the farmers. Government of India issued a policy on 'Kissan Drones' in March, 2022 inaugurating 700 of them by the Hon'ble Prime Minister of India through Agri Start-UPS. The policy enables gram panchayats to deploy drones in 100 districts of the country. Earlier in 2016, ICAR through IARI formulated a collaborative project 'Sensagri: Sensor based Smart Agriculture' to develop indigenous prototype drones for crop and soil health monitoring. Spraying of agrochemicals, direct seeding of crops, detecting crop anomalies are some of the areas where drones are presently used by farmers. Many private players like 'Senseacre labs', 'Marut', incubates of International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) provide services to farmers, research organization, FPOs in crop health monitoring, weed detection, pest detection, volumetric analysis and disaster management.

3.7 Food Safety

Food safety and quality assurance in the food industries place a high priority on the detection of food quality. The traditional methods for determining food quality are time-consuming, laborious, destructive, and labor-intensive. The development of non-destructive technologies in food quality assessment is helpful for gathering quantitative and qualitative data without destroying the sample. The rapid advancement of non-destructive techniques for assessing food quality includes imaging-based, spectroscopy-based, and other pertinent applications including electronic tongue, electronic nose, and dielectric techniques.

One example is 'PureScan AI' that has developed 'AflaScan', a rapid and non-destructive aflatoxin measuring device, with a variability of 1 ppb. This technology uses image processing under ultraviolet (UV) light. It is intended to assist exporters, traders, processing businesses, and retailers in making quick judgements regarding transactions and purchases.

3.8 Crop yield forecasting and planning

Remote Sensing using satellite allows for accurate crop forecasting as well as regular crop monitoring. The data can also help alert farmers to local issues such as irrigation or fertilization. Satellites can predict and assess early detection of water and nutrient stress, pests and disease incidence, flood damage, heat and cold stress and help in taking timely measures saving the crop from huge losses.

EOS Data Analytics (EOSDA) is a global provider of AI-powered satellite imagery analytics. EOSDA team of data scientists and engineers have developed effective techniques for crop yield estimation using remote sensing and machine learning models. The data basis for EOSDA is earth observation data retrieved from satellites to cover areas ranging from individual farms to regions. Cropin and SatSure Technologies use satellite applications to tailor make recommendations on crop insurance, farm inventory management, trading and input processing.

3.9 Farmer Producer Organizations (FPOs)

A growing amount of evidence indicates that access to agricultural guidance can help farmers enhance their incomes by adopting strategies on input cost reduction and increasing their revenues by aggregating their outputs. FPOs provide the institutional mechanism for ease of technology transfer and to reach out to large number of small holder farmers.

Kalgudi is a free online multi-tasking platform for agriculture marketing for producers, buyers (traders), service providers, input companies, members in FPOs. Individual accounts are created for personalized advice on crop selection, schedule of agricultural activities, inputs and market availability. Kalgudi enables decision support system for famers and self-help groups through collaborations with research and development institutes like ICRISAT, ICAR and State Agricultural Universities. Keansa Technologies, an incubate of ICRISAT worked with FPOs in Andhra Pradesh and Odisha by digitizing their operational efficiency.

4. Digital Technologies for Accelerated Crop Improvement

4.1 Precision Phenotyping

Digital technology tools are advancing agriculture with breakthroughs in artificial intelligence are accelerating the pace and success of plant breeding innovations by accurately predicting genetic outcomes during trials. High-throughput phenotyping (HTP) is a quick and non-destructive method for tracking and measuring a variety of phenotypic variables linked to growth, yield, and stress tolerance (Tariq *et al.*, 2020).

Breeders and growers are starting to employ imaging technologies more frequently to evaluate the quality or stage of development of their products. Imaging systems are being utilized for a number of tasks such as sorting by size, height, and width. However, these technologies can identify plants that perform variably for photosynthesis using physiological indicators like the chlorophyll index and anthocyanin index through multispectral and laser-based sensors. Due to early evaluation and more accurate measurements, these new technologies will hasten crop breeding programs.

LeasyScan (located in ICRISAT campus, Hyderabad) is one such high-throughput phenotyping technology created to quickly assess leaf area in order to gain access to the dynamics of leaf development and leaf conductance. It enables more thorough analysis of plant phenotypes and rapid development of enhanced, drought-tolerant crops through large-scale plant screening. LeasyScan has the ability to scan 3200–4800 individual plots with in a time span of two hours. Leasyscan is used in several crop breeding programmes which reduces the time taken in breeding a new and improved varieties (Akinlade *et al.*, 2022; Srivastava *et al.*, 2022).

4.2 Predictive tools for mapping crop suitability

Understanding the spatial structure of crop adaptability is essential for determining where solutions might be used to increase crop system efficacy. The basis of sustainability plans for boosting food production is knowledge of where to implement with a fair chance of success.

The Crop Suitability Mapping tool provides crop suitability for any location on the earth for 18 different crops based on soil characteristics and climate factors (Peter *et al.*, 2020). For example, it provides maps that illustrate the spatial expansion of a particular variety of crop that can survive higher temperatures.

4.3 Early Detection of Pest and Diseases

Timely and accurate detection of disease and pest is important in order to reduce qualitative and quantitative crop losses. Early diagnosis will give time to manage biotic stresses and reduce the losses incurred in farms. Automated methods for an early detection of plant diseases are vital for precision crop protection.

AgNext Technologies, a Punjab based startup is using IoT based solutions towards precision farming. They have combined four technologies – IoT, AI based image processing, weather forecasting and satellite imagery to create a single solution platform for stakeholders to monitor and predict occurrence of pests and diseases.

4.4 3D Technologies

Structure from Motion (SfM), a photogrammetry technique can use modern smartphones that capture 2D images and transform them into a 3D point cloud data. This is similar to using a LIDAR camera and determine volumetric information. Smartphone-based SfM studies have the ability to more accurately and efficiently estimate the yields field crops like Sorghum. A proof of concept was performed to predict Sorghum yields which higher accuracy to become an alternative to Crop Cutting Experiments in the future.

5. Digital Technologies for Investments & Policy

5.1 Carbon farming

Given the commitments of the global community for carbon neutrality; agriculture provides an opportunity for carbon as a new crop for the farmers. Carbon farming is a whole farm strategy to improving carbon capture on landscapes by employing techniques that are known to increase the rate at which CO_2 is extracted from atmosphere and stored in plant material and/or in soil organic matter (Sharma *et al.*, 2021).

'Farm Carbon Toolkit' is an independent, farmer-led firm that assists farmers in measuring, understanding, and reducing their greenhouse gas emissions while enhancing the future sustainability of their operations. Through their online platform, they offer tools and services for measuring effect and managing initiatives with farmers that inspire action.

The main obstacle to connecting farmers with carbon markets is data. When it comes to developing solutions to close the data gap in agriculture and carbon farming, SourceTrace has almost ten years of experience. CarbonTrace estimates the farm carbon credits using the data generated by Source Trace technology.

5.2 MRV platforms

Monitoring, Reporting, and Verification (MRV) is a multi-step procedure for calculating the amount of greenhouse gas (GHG) emissions that have been reduced by a particular mitigation activity over time, such as lowering emissions from regenerative farming practices, deforestation and forest degradation, and reporting these results to a third party that has been approved (Woo *et al.*, 2021). Based on such review reports, the third-party issues credits and these credits are monetized using MRV. As measured in tonnes of CO_2 equivalent, one credit is equal to one tonne of decreased GHG emissions (tCO_2eq).

The Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants and the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) supported the programs on GHG Mitigation Options in agriculture, which is the source of the data sharing platform called as AgMRV (Shuetz & Poulos, 2021). Through national planning and development initiatives, the project seeks to enable large-scale mitigation by lowering methane (CH_4) emissions from rice producing systems in Bangladesh and Vietnam. Recently, several organizations and agencies have initiated the carbon credit programs in agriculture. For example, Grow Indigo Private Limited in collaboration with CIMMYT, ICAR-IARI, ICRISAT and state governments have initiated such programs in India.

5.3 Fintech products

In response to the increasing importance of financing agricultural technologies, the term "Agri Fintech" was coined (Agarwal, 2022). The vast potential of farmlands lies unrealized in the absence of funding.

FarmDrive a mobile application employs data analytics to link smallholder farmers with lenders and loans, promoting the growth of both crops and farmers. Farmers can increase their credit worthiness by using technology that allows them to track their earnings and expenses via their mobile phone.

Jai Kisan's 'Bharat Khata' offers services for rural individuals' and enterprises' financial needs, starting with the most suitable loan options. It works with value chain companies of all shapes and sizes, from little shops to big firms, to offer financial services to their network of middlemen (dealers, aggregators, etc.) and individual clients, fostering growth for all.

5.4 Block chains

Block chain technology creates a secure database of assets and transactions that enables peer-to-peer exchanges of money, goods, and anything else of value in an open and transparent manner (Woo *et al.*, 2021; Alobid *et al.*, 2022). The complexity and distinctive qualities of block chain make it a desirable solution for identifying, storing, and tracking anything of value.

With the goal of improving visibility and responsibility throughout the food supply chain, IBM Food Trust brings together growers, processors, wholesalers, distributors, manufacturers, retailers, and other parties. This system, which is based on IBM Block chain, links parties through a shared, permissioned record of food origin, transaction information, processing information, and more.

5.5 Farmer profiling

Digital data collection is the starting point for contributing to a digital ecosystem for farmer profile data. Farmer Data Profiling is the process of gathering all of the profile information of the farmers under an organization's umbrella and then leveraging this information to support the development of services.

Samunnati is a farmer profiling platform that aims to put smallholder farmers at the centre of India's agriculture. Samunnati promotes collective development and prosperity for the agricultural ecology. Through several technology-enabled interventions and cooperative alliances, Samunnati's Agri Commerce and Agri Finance solutions, which serve the full value chain, help associated Farmer Collectives and the greater ecosystem be more effective and productive.

6. A Digital Way Forward

Digital technologies are steadily transforming agriculture into a data driven, informed and structured industry which opens avenues to meet the climate and food crisis challenges. The advent of digital agriculture services in smallholder contexts is expected to have an impact on the behavior of farmers in their production and consumption decisions, social interactions, decision making, bargaining power and also impact the transactional relationships of farmers with input providers, processers, retailers, peers etc. The Agriculture 4.0 incorporates the evolution of precision farming and refers to all actions that are carried out in agriculture based on precise and accurate analysis of data and information collected and transmitted through advanced tools and technology.

Future Research areas under Digital Agriculture 4.0

- Conduct cutting-edge research on the technical and social dimensions of digital agriculture, specifically on how and what information will lead to practice change, gaining of efficiencies and overall impacts on farm livelihoods
- Answer how and what information & digital technologies might be delivered to create new services for smallholder farmer needs and their farming system-based value chains
- Support developmental efforts to build new partnerships for enhanced development impact using digital platforms and tools particularly through public-private-partnerships
- Setting up of centers for excellence (CoE) in agri-digital transformation and an enabler, disseminator and a mediator of knowledge sharing and innovation through updated digital applications, including piloting of virtual-educational, library and learning programs

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National Symposium on Digital Farming: The Future of Indian Agriculture
2-3 February 2023, ICAR-IISS, Bhopal

Role of Geospatial Technologies in Fertilizer Recommendation for Enhancing Crop Production and Soil Health

Pradip Dey

ICAR Indian Institute of Soil Science, Bhopal - 462 038, Madhya Pradesh

Email: pradipdey@yahoo.com

ABSTRACT

The use of geospatial technologies for the enumeration of soil spatial variability and preparation of GPS/GIS-based soil fertility maps helps in the decision-making processes regarding the precise use of plant nutrients by adopting variable rate technology. Sampling strategy and semivariogram modelling for minimizing the error of soil fertility appraisal from the linking of models and GIS has been discussed. A brief history of soil fertility mapping in India as well as geo-referenced soil fertility mapping of 173 districts through stratified random sampling method and the use of such maps for developing customized fertilizer solutions has also been deliberated. Geospatial technology-based appropriate interpolation techniques to assess soil fertility were discussed with a suitable case study. It was observed that lognormal kriging gave better results where the coefficient of skewness was larger than one. Further uses of geospatial technologies for the development of customized fertilizer recommendations have been contemplated.

Key words: Customised fertilizers, DSS, GIS, GPS, Interpolation methods, Semivariogram, Soil fertility mapping

With the shift towards globalization, the need for precise and reliable agricultural information has become more inevitable in the decision-making processes. For the use of natural resources efficiently, a database is of utmost importance. The exponential growth of population in a country like India demands the maximum possible output of food and fiber from the existing cultivated land area. Since total factor productivity and fertilizer response ratios are declining in all the states, new innovative technologies are to be followed to arrest the decline in factor productivity. It was observed that the adoption of ICT, incorporating externalities for making economic decisions, accounting for capital invested in the face of climate change, strengthening local and community governance structures, and developing of voluntary guidelines on sustainable land management in sync with local law are essential elements for the development of sound soil policy (Dey, 2020). There is an urgent need for the adoption of efficient nutrient management harnessing geo-spatial technologies like global positioning systems (GPS), geographical information systems (GIS), remote sensing, geostatistics and variable rate applicators to optimize various agricultural inputs (Dey and Bhattacharyya, 2021).

A GIS is a powerful set of tools for storing and retrieving at will transforming and displaying spatial data from the real world for a particular set of purposes. Like any other information technology. Functions of GIS include data entry, data display, data management, information retrieval, and analysis. The applications of GIS include mapping locations, quantities and densities, finding distances and mapping and monitoring change. The availability of GPS/GIS interfaces

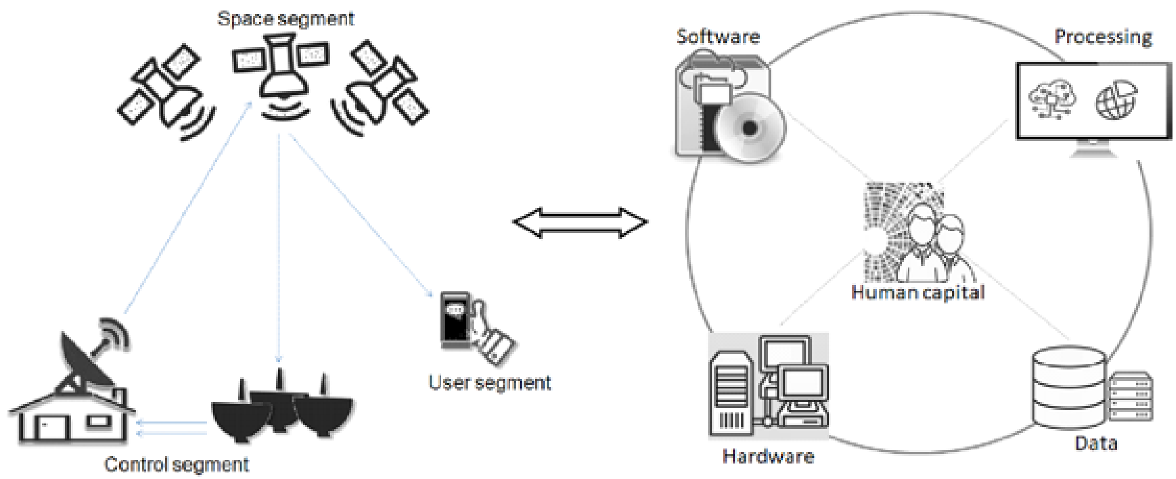

Figure 1. Geospatial interface for development of soil fertility maps

(Figure 1) to agricultural applications eventually made it possible to manage very small units rather than managing the field as average.

In many instances, soil differences and yield monitors justified the expense of the GPS/GIS technology as increased yields were achieved with lesser inputs. Additionally, the environmental cost of over-application was lessened especially in the case of nitrate and phosphorus fertilization. GPS/GIS-based soil fertility maps will also be useful for the planners, administrators in the government, fertilizer and other input manufacturers/suppliers and extension workers of the Department of Agriculture of different State Governments.

The wealth of data has been generated for delineating the soil fertility of India over the years (Ramamoorthy and Bajaj, 1969; Dey and Sekhon, 2016; Dey *et al.*, 2017a). Mapping of soil fertility status can be carried out using GIS very effectively. One of the procedures follows simple map reclassification techniques and the other follows point data modeling using the interpolation technique. The flow chart (Figure 2) below shows the pathways for map generation using the map reclassification technique.

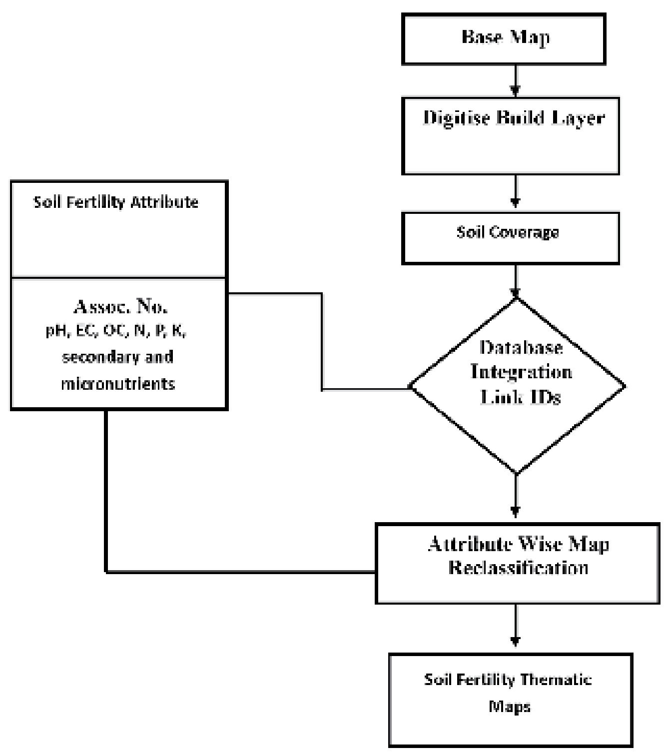

Figure 2. Flowchart for GPS/GIS-based map generation

Soil spatial variability

Kriging

Kriging is the Geostatical method of predicting values at unknown points. Kriging is similar to other interpolation methods. The semivariogram plays a crucial role in kriging.

The actual location of the selected soil samples recorded using GPS during sampling is used for kriging. The method of Kriging is based on the regionalized variable theory that assumes that the spatial variation in the phenomenon represented by the 3 values is statistically homogenous throughout the surface i.e., the same pattern of variation can be observed at all locations on the surface. This hypothesis of spatial homogeneity is fundamental to the regionalized variable theory.

Semivariogram

Semi-variance is a measure of the degree of spatial dependence between samples. Basically, it measures the average reduction in the resemblance between two random variables with increasing distance. The magnitude of the semi-variance between points depends on the distance between the points. A smaller distance yields a smaller semi variance and a larger distance results in a larger semi-variance. The plot of the semi-variance as a function of distance from a point is referred to as a semivariogram (Figure 3). The spatial variation is quantified by the semivariogram.

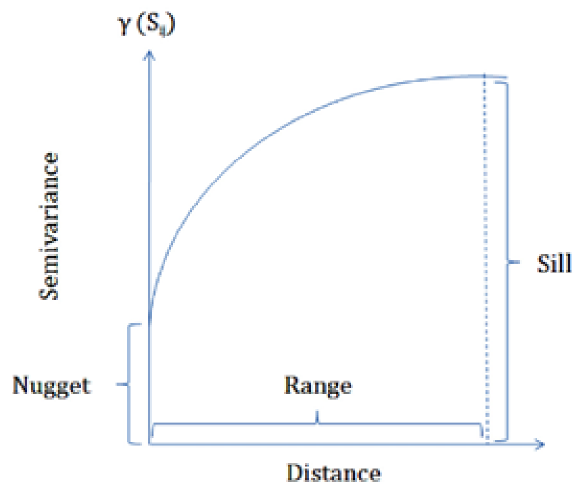

Figure 3. Illustrated semivariogram showing sill, range and nugget

Sill: Point where the curve levels off (inherent variation where there is little autocorrelation)

Range: Lag distance where the sill is reached (over which differences are spatially dependent).

Nugget: Initial semi-variance when autocorrelation is the highest (intercept); or just the uncertainty where distance is close to 0.

The study of soil spatial variability under an agroforestry system in sodic soil using geo-statistical methods reveals that the semivariogram parameters are a very effective tool to estimate soil physico-chemical properties (Saha *et al.*, 2017). For better results and to minimize the error of soil fertility appraisal from the linking of models and geographical information systems, the basic assumptions, methods, scale, control parameters and type of input data are important. Five semivariogram models, viz., linear, spherical, exponential, circular and Gaussian models are important. The spherical model (basically a modified quadratic equation) is one of the most prevalent models used in semi-variogram modelling, in which spatial dependence levels off as sill and range. In the linear model, spatial variation continues to increase with distance. The Gaussian model is based on a normal probability distribution curve. In the circular model, the spatial dependence disappears at asymptotic level.

Sampling strategy

Sampling is the first step of soil fertility evaluation, mapping and soil health card generation. These activities can be used for deciding nutrient management for precision agriculture and to arrive at decisions on the plant nutrient management strategy of the area. Also, such maps may be used for soil quality assessment over a period of time by periodical assessment from the same GPS points to ascertain whether the soil quality is sustaining or aggrading, or degrading. Sekhon *et al.* (2017) have developed a new method for computing reliable sample size for prescribing soil test-based nutrient management interventions. In addition, we need to have better tools for tracing the soil samples collected for the SHC Scheme with precise GPS tagged for better delivery of quality recommendations and pin-pointing/correcting sources of error (Dey, 2019b).

Grid sampling is an unbiased and relatively quick method of obtaining soil samples and generating location-specific soil management recommendations. There are softwares to facilitate it. After the samples have been pulled from georeferenced sites and analysed, a map is made by either filling in the grid cells with the soil test value (grid cell method) or assigning the soil test value to a point and then interpolating between points (grid point method). Grid sampling results in either a 'checkerboard' map (grid cell method) or a 'smoothed' map (grid point method). The ultimate aim is to prepare maps for deciding on management strategies regarding the assessment of plant nutrient status, diagnose suspected nutrient imbalances, monitor the effects of management on crop nutrient status and soil fertility, assess the availability of toxic elements and provide a basis for making fertiliser recommendations for increasing crop yield and improving quality, improving fertiliser use efficiency, decreasing impacts on water quality and improving soil quality. However, there are shortcomings in this approach too. The glitches include the absence of unanimity on appropriate grid size and mode of determining the same. Also, there are instances of unduly biased results by localized irregularities of maps prepared from grid samples. Further, uniform grids are susceptible to systematic errors and result in both under/over-sampling if soil regions vary in size. There is also the danger of grid cell sampling results in cells being averaged over dissimilar soil types. Unfortunately, localized irregularities are encountered more often than not under field conditions. Farmers are more aware of such irregularities in their respective fields. Hence, the participatory sampling process has enough scope for scaling up in other regions.

The deficiencies can be minimized by the adoption of appropriate sampling and intensity of management through directed sampling. The realization of the fact that involving farmers, the major stakeholder in any agri-based project, is the key to faster adoption and implementation of technology, a directed sampling process has been followed in the GIZ-NABARD ProSoil project of Mandla and Balaghat with strong participation of the community (ProSoil Newsletter, 2018). In the process, it was possible to integrate the experience and wisdom of people about their soils, parcel of land, productivity, etc. with scientific knowledge to arrive at a robust approach. The farmers' experiences not only lead to more knowledge but also more fine-tuning of the maps with their understanding of yields, topography, water retention capacity and soil health management history. It was thus possible to make appropriate clusters for developing soil fertility maps with their understanding of their own lands. The added advantage of the participatory directed sampling process is that it captures localized irregularities better and hence, the decision arrived at from this process is superior.

Use of Geospatial Technology for Soil Fertility Mapping in India

Soil fertility maps based on a nutrient index

The earliest soil fertility maps were developed by Ramamoorthy and Bajaj (1969); thereafter, Ghosh *et al*. (1980), Motsara (2002) prepared soil fertility maps. Muralidharudu *et al*. (2011) prepared soil fertility maps based on nutrient indexing (NI) from soil fertility data of soil testing laboratories (Figure 4), where NI= $[3N_H+2N_M+N_L] / [N_H+N_M+N_L]$.

However, none of these maps are GPS based and hence, there is hardly any chance of going back to the earlier site to monitor temporal changes. Later on, based on the stratified random sampling method, geo-referenced soil fertility maps of both macro- and micro-nutrients of 173

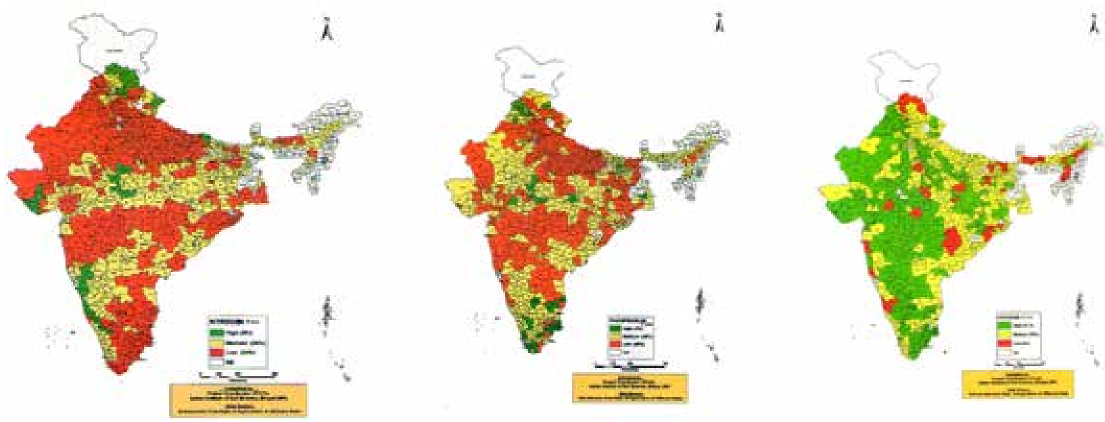

Figure 4. Nutrient index-based soil fertility map of India

districts of India has been completed by ICAR-IISS, Bhopal in collaboration with mainly AICRP (STCR) centres (Basavaraja *et al*., 2016, 2017; Chitdeshwari *et al*., 2017; Dey *et al*., 2017b; Maragatham *et al*., 2014; Mishra *et al*., 2015, 2016, 2017; Santhi *et al*., 2018; Sellamuthu *et al*., 2015; Sethy *et al*., 2019; Singh *et al*., 2015a, 2016). As an illustration, the GPS/GIS-based soil fertility maps of the Villupuram district of Tamil Nadu have been shown (Figure 5).

These fertility maps can be used for deciding nutrient management at the macro level. Also, such maps may be used for soil quality assessment over a period of time by periodical assessment from the same GPS sites for determining whether the soil is sustaining or aggrading, or degrading. Further, based on the soil fertility status, different adaptive management tools can be selected to avert further soil degradation.

Use of GPS/GIS-based soil fertility mapping for interpolation: a case study from Madhya Pradesh

The selection of the best interpolation technique to assess soil physico-chemical properties of any unsampled location is very important. It is critical to choose the optimum interpolation technique for assessing soil physico-chemical parameters in any unsampled area for use in plant nutrient decisions. A case study was undertaken for the eastern part of Madhya Pradesh to determine the suitable interpolation technique for mapping soil properties, the inverse distance weighting (IDW), ordinary kriging (OK), and spline were compared and analyzed (Dey, 2017b; Kanwaria *et al*., 2021). Relationships between the statistical properties of the data were analyzed using soil tests of pH, electric conductivity, organic carbon, nitrogen, phosphorus, potassium, sulfur, and zinc, from 2150 different locations (0–15 cm). For inverse distance weighting and spline, we used exponent values of 1, 2, and 3, and these values were decided from the RMSE value. The ranges of 5–30 closest neighboring points were selected for interpolation methods. Out of total of 2150 samples, 10% points were preserved for validation using the root mean square error (RMSE) test. Overall, all of the methods gave similar RMSE values. In this study, ordinary kriging (exponential) performed well for pH, K, and S, whereas IDW was best for OC, N, and P while spline was for EC and Zn. In all uses of IDW, the power of one was the best choice; it is possibly due to the low skewness in OC, N, and P. In all circumstances, a significance of three was established to be the best control for splines. Lognormal kriging gave better results where the coefficient of skewness was larger than one. It was concluded that many parameters can be better ascertained from the RMSE value obtained from validation.

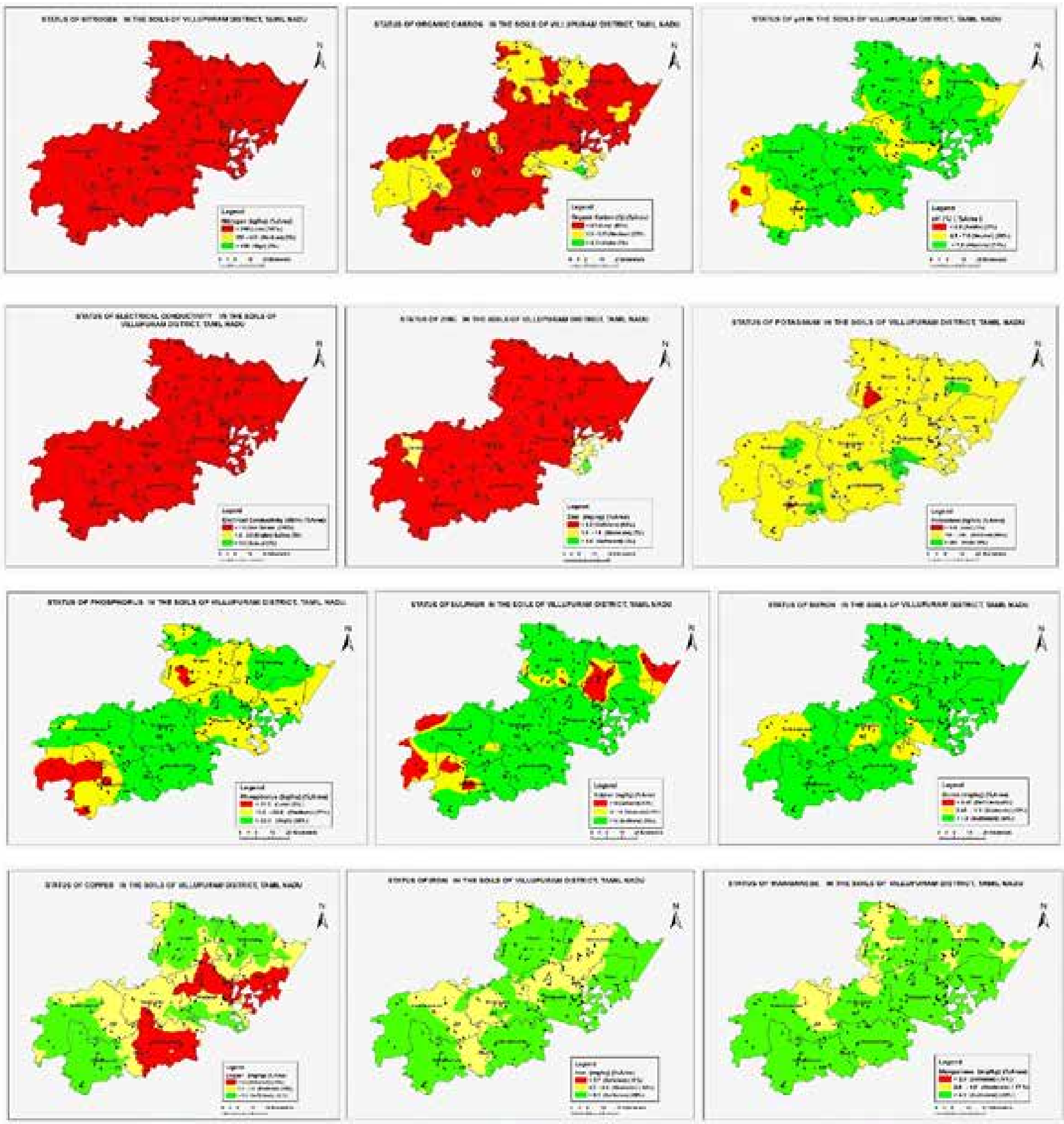

Figure 5. GPS/GIS-based soil fertility maps of Villupuram district of Tamil Nadu

Use of geospatial technology in decision support system (DSS) for fertilizer recommendation

***DSSIFER*:** Decision Support System for Integrated Fertiliser Recommendation (DSSIFER) is a user-friendly software encompassing soil test and target-based fertiliser recommendations through Integrated Plant Nutrition System developed by the AICRP-STCR, Department of Soil Science and Agricultural Chemistry, TNAU as well as the recommendations developed by the State Department of Agriculture, Tamil Nadu. If site-specific soil test values are not available, data-base included in the software on village fertility indices of all the districts of Tamil Nadu will generate soil test-based fertiliser recommendations (Dey, 2019a). Using this software, fertilizers doses can be prescribed for about 1,645 situations and for 190 agricultural and horticultural crops along with fertilisation schedules. Besides, farmers' resource-based fertilizer prescriptions can also be computed. Therefore, adoption of this technology will not only ensure site-specific balanced fertilisation to achieve a targeted yield of crops but also result in a higher response ratio besides sustaining soil fertility. In addition, the software also provides technology for problem soil management and irrigation water quality appraisal. Moreover, Soil Testing Laboratories of all the organisations can generate and issue the analytical report and recommendations in the form of Soil Health Cards (both in English & Tamil) which can be maintained by the farmers over the long run.

***Web-based fertilizer recommendation system*:** Web-based fertilizer recommendation system through a targeted yield approach coupling with geo-referenced soil fertility maps of Tumkur district has been developed by UAS, Bengaluru centre of STCR in Karnataka. Through this DSS, farmers get the fertility status of their land just by entering the geo-coordinates of their land which is now available in all smart/ android phones (GPS app) which are commonly used by the farmers. In addition to the STCR approach, the software has a provision to provide a nutrient recommendation based on the LMH/STL approach. This software gives the fertility status of the soil even up to 100 m distance throughout the district wherever geo-referenced maps are available and thus saves the time and cost required for frequent soil sampling and analysis (Dey, 2019a). It is dynamic software with the provision of fine-tuning for more accuracy by the addition of more number of soil analytical data obtained under the Soil Health Card Scheme for the district. The framework of this software is further being utilized for other districts of Karnataka for fertilizer recommendation based on STCR targeted yield approach.

Use of geospatial technology for the development of customised fertilizers

The concept of balanced use of fertilizers to promote site-specific nutrient management can be achieved through customised fertilizers. The customized fertilizer formulations can be derived from basic data of STCR and clustering of response zones through GPS/GIS-based fertility mapping helped in encouraging the balanced use of fertilizer application, better nutrient use efficiency, and higher profit in the hands of farmers (Dey, 2019a). STCR has already proved to be beneficial for different cropping systems for increasing crop yield and maintaining soil health (Singh *et al*., 2015b, 2017, 2018). The steps involved to arrive at customized grades are, (i) geo-referencing of chosen area, (ii) selecting sampling points based on appropriate statistical procedure, (iii) actual sampling of the sites, (iv) analyzing soil, plant and water samples for nutrients and some soil characteristics, (v) development of customised soil fertility maps using GIS, (vi) defining management zones, (vii) yield targeting in major management zones, (viii) computing crop removal of nutrients, (ix) calculating nutrient requirement (amount and ratio), (x) blending of nutrients based on the generated information, and finally (xi) minor adjustment for physical stability of customised grades.

The per cent contribution from soil and fertilizers was determined by using AICRP on Soil Test Crop Response (STCR) data-base and applied for the respective crop. This value was then corrected for nutrients available from the soil and for the fertilizer nutrient utilization efficiency (determined by using the STCR equation) by the respective crop. The secondary and micronutrients were included in the above-derived grade through nutrient indexing method and prevalent deficiency. The technology developed has been adopted by Indo Gulf Fertilisers, Jasdishpur, Coromandel Fertilisers and NFCL, Hyderabad. For example, the customized grades were finalized in a consultancy project under PPP mode with M/s. IndoGulf Fertilisers, Jasdishpur. It was observed that sulfur, zinc and boron was deficient in the soils of these districts. Based on this observation, the micronutrient zinc (Zn), boron (Zn) and secondary nutrient sulfur (S) were included in NPK-derived values to arrive at the following customized fertilizer formulations:

For Maize, NPKSZnB 14:22:12:05:0.5:0.05 in a cluster of districts, viz., Purnia, Kathiar, Araria, Kisanganj, Siwan and Saran; NPKSZnB 11:21:16:05:0.5:0.05 in a cluster of districts, viz., for Muzaffarpur, Vaishali, Madehpura, Saharsa and Supaul of Bihar. For potato, NPKSZnB 12:16:18:06:0.6:0.1:0.5 in a cluster of districts, viz., Murshidabad, Malda, Nadia, Bankura, Birbhum and West Midnapur; NPKSZnB 12:16:22:06:0.6:0.1 in a cluster of districts, viz., Howarth and North 24 Parganas of West Bengal. Further, 7 Customised Fertiliser Grades (CFG) of cotton, rice, maize and sugarcane were developed for a separate cluster of districts of Maharashtra, Andhra Pradesh, Karnataka and West Bengal through a consultancy project with M/s. Nagarjuna Fertilisers and Chemicals Limited, Hyderabad.

These customized were included under Fertiliser Control Order vide Department of Agriculture & Farmers Welfare, GoI notification S.O. 350(E) and S.O. 359(E).

Conclusion

The use of geospatial technologies for the enumeration of soil spatial variability and preparation of GPS/GIS-based soil fertility maps helps the adoption of variable rate technology (VRT) for the application of plant nutrients and amendments by automated rate settings on applicators/ equipment with input-saving and profit maximization. GPS/GIS-based soil fertility maps together with STCR prescription equations can also be used for the development of customized fertilizer formulations and decision support systems for improving crop productivity and maintaining soil health. In addition, leveraging private investment and initiative is of utmost importance for the development of customized fertilizers and the adoption of VRT. Further, this will help in halting and reversing land degradation as well as sequestering soil organic carbon for transitioning to achieve land-degradation neutrality (LDN) as enshrined in Target 15.3 of SDG.

Acknowledgement

The author expresses sincere thanks to the Department of Agriculture & Farmers Welfare, GoI for the financial support, the Indian Council of Agricultural Research, New Delhi for guidance and SAUs for technical collaboration in the project entitled “GIS and GPS based soil fertility evaluation for precise fertilizer recommendations” (Project Code: 4001/439).

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National Symposium on Digital Farming: The Future of Indian Agriculture
2-3 February 2023, ICAR-IISS, Bhopal

Key to Tackling Climate Change: Adaptation and Resilience in Agriculture

Kamaljit Ray

Advisor, Ministry of Earth Sciences, Prithvi Bhavan, Lodhi Road, New Delhi-110 003

1. Introduction

Transition to sustainable agriculture to meet the world's food demand projected to increase by at least 60 percent above 2006 levels, under the climate change scenario is a challenge. To keep the increase in global temperature below the crucial ceiling of 2°C, emissions will have to be reduced by 70 percent by 2050. This can only be achieved through the large participation of the agriculture sector. As per the FAO report on the impact of disasters on agriculture and food security, the full impact of disasters on the agriculture sector due to weather extremes is not well understood but still, 25 percent of the economic impact caused by climate-related disasters falls in the agriculture sector. Agriculture gets affected due to the impacts of climate change on soil, land, water, and atmosphere. Agriculture is also a significant contributor to Greenhouse gas emissions directly or indirectly.

2. Climate Change Impact

Climate change is impacting agriculture through the increased frequency and intensity of extreme climate events like heatwaves, floods, droughts, etc. (Ray, 2019, 2021). The 10-year average for the period 2013-2022 is estimated to be 1.14 [1.02 to 1.27] °C above the 1850-1900 pre-industrial baseline. Ocean heat was at record levels in 2021 (the latest year assessed), with the warming rate particularly high in the past 20 years. There had been a 7 percent reduction in emission of greenhouse gases due to COVID19 pandemic related lockdown, in 2020, in different parts of the world. Howsoever the concentration of greenhouse gases continued to rise because of the long lifetime of CO_2 in the atmosphere. The temperatures have also shown rising trends in India. As per the latest data released by IMD (2022), The annual mean land surface air temperature averaged over India during 2022 was +0.51°C, above the long-term average (1981-2010 period). The year 2022 was the fifth warmest year on record since nationwide records commenced in 1901. However, this is lower than the highest warming observed over India during 2016 (anomaly of +0.71°C) and higher than the previous year 2021 (anomaly of +0.44°C). Global mean temperature in 2022 is currently estimated to be 1.15 ± 0.13 °C above the preindustrial (1850-1900) average, likely making the past eight years (2015-2022) the warmest on record. Despite La Niña conditions keeping global temperature low for the second consecutive year, 2022 is still most likely to be 5th or 6th warmest year on record. Climate action failure is one of the top global risks of 2021, both in terms of likelihood and impact (Table 1).

3. Impact of climate change on agriculture eco-systems

To achieve the projected demand as per the rising population, the global crop production needs to double by 2050 with a 24 percent rate growth of crop production per year. Climate change may reduce yields of staple crops by up to 30 percent due to low productivity and crop failure. Widely

Table 1. Global Risks of 2021 (World Economic Forum, 2021)

Top Global Risks by Likelihood	Top Global Risks by Impact
Extreme weather	Infectious diseases
Climate action failure	Climate action failure
Human environmental damage	Weapons of mass destruction
Infectious diseases	Biodiversity loss
Biodiversity loss	Natural resource crises
Digital power concentration	Human Environmental damage
Digital inequality	Livelihood crises

cited estimates show that climate change has already negatively affected wheat and maize yields. India is witnessing a rice yield increase of only 1 percent per year and a 1.1 percent increase per year in wheat yields. Thus, the yield driven production growth in India is nearly unchanged per capita rice and wheat harvests. With global warming, the projected groundnut crop failures increase by a factor of two, in south India, while west, central and east India are projected to have reduced crop failures. Eastern and northern India are the locations most at risk, but parts of central and western India may benefit from increased precipitation (Mishra, 2014).

Models have indicated the increase in precipitation in the monsoon climate (particularly India) correlates with the decreasing irrigation water demand (IWD) thus compensating the temperature rise (warming). However, above 4^{o} C warming, IWD tends to increase with rising temperature. In India, in certain states, irrigation has reached a threshold beyond which it may not be able to compensate for the impacts of warming. The climate change-induced increased evaporative demand may accelerate the drought condition in the North-West part of South Asia in the 21st century. The negative impacts of climate change on soil fertility and mineral nutrition of crops would far exceed beneficial effects, which would intensify food insecurity, particularly in developing countries (Zhai *et al*., 2020).

4. Resilience for Sustainable Development

Agriculture risk assessments hold a key in identifying risk management strategies today and building resilience tomorrow. There is a need to develop a resilience-based holistic system approach to avoid losses and build a risk management capacity at production, market, and enabling environment levels for sustaining global agriculture and food systems. The sustainability of agriculture depends upon the availability of natural resources that support agriculture presently and also in the future. The management of these resources despite the disruptions due to climate change and associated weather extremes would be a challenge. Development of new adaptation techniques and strategies for agriculture and surveillance of resources would be needed to tackle the adverse effects of climate change. The negative impacts of extreme events such as tropical cyclones, droughts, and ûoods on agriculture are well known and well documented but there are also several positive impacts of extreme events on agriculture (Ray *et al*., 2019). These include increased rainfall to inland and coastal areas from tropical cyclones, recharging the soil moisture and provision of extra storage in rivers, ponds, and lakes, which can be utilized for irrigated agriculture, the ûxing of atmospheric nitrogen by thunderstorms, maintenance of the fertility of ûoodplain soils due to ûooding, etc. A comparison of all India annual rainfall (mm) and total food grain production departure for the last seventy years showed that, in the last decade, the food-grain production has become more or less resilient to rainfall amount (Fig. 1).

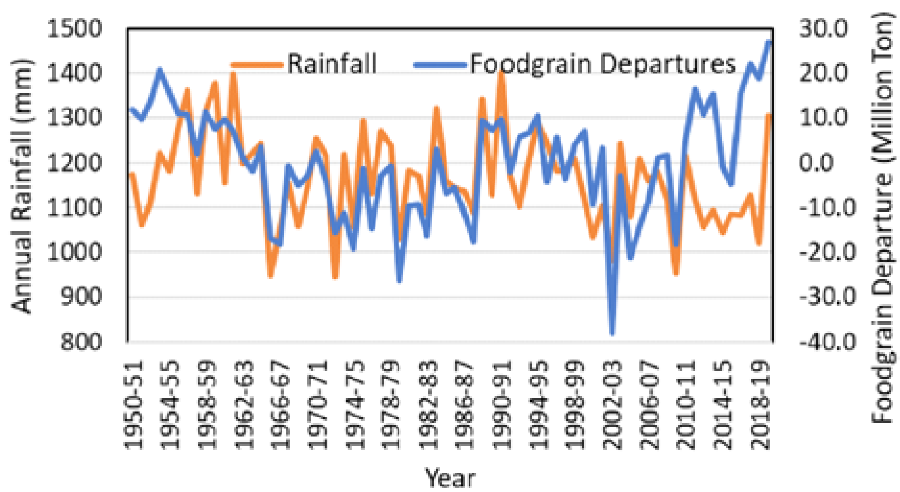

Figure 1. The pattern all India annual rainfall (mm) and total food grain production departure for last seventy years. The rainfall is for calendar year and food grain production is for agricultural year (June-May)

Water for agriculture will need to be better managed for it to contribute to reductions in poverty and vulnerabilities. This management will need to consider not just quantities of water, but the quality of the water and the multiple agricultural (e.g., staples vs. cash crop) and non-agricultural uses. Better-managed irrigation can be an important climate-change adaptation strategy in agriculture that supports improvements in yields and provides other benefits. These measures include farm-level investments in efficient irrigation technologies, deficit irrigation, water harvesting, micro-irrigation, minimum tillage, and improved water delivery systems. Understanding the micro-level adaptive responses of farmers to climate change is important for ensuring that publicly planned adaptation investments have broader impacts (UNEP, 2021). Globally, there is over-abstraction of groundwater and to reduce the overexploitation of groundwater, pumping and water-use behaviors in many regions will need to change (Balasubramanian, 2020). Rao *et al*. (2019) in their study identified 30 sustainability indicators for climate-resilient agriculture in India that are particularly suitable for different agroecosystems of the sub-continent.

The following section briefs about various government programmes, which try to enable agriculture resilient to the negative impact of climate change.

4.1 National Level Programmes for Climate Change Resilience in Agriculture

An Inter-ministerial committee constituted by the Government of India in 2016 (MoA&FW, 2017) on Doubling of Farmers Income, noted in their report an impressive agricultural growth since 1947, indicating farmers resilience to multiple challenges including climate variability. However, the sustainability of agriculture growth is a major concern. The report examined the poorest 150 districts based on farm income and climate vulnerability and suggested special attention in terms of the technology package, infrastructure, and policy support for them. Some 29 districts were found to be highly vulnerable in terms of double stress arising from low farm income and high climate vulnerability. The country's agriculture structure is dominated by small and marginal farmers, accounting for 85 percent of the total number of landholdings. The adverse impact of climate will be more on smallholding farmers. The committee recommended that deployment of appropriate technology will bridge yield gaps, negotiate negative impacts of climate change and overcome constraints of water, soil, and other resource deficiencies (MoA&FW, 2018). India, with a large population dependent on agriculture dominated by small landholders, is among the countries more vulnerable to climate change. National Innovations in Climate Resilient Agriculture (NICRA) programme of ICAR has done a district-level vulnerability assessment of Indian agriculture to climate change which will help policymakers to enhance the resilience of Indian agriculture to climate variability and change through strategic research and by promoting adaptation technologies (Rao *et al.*, 2019). The government of India has many national-level programmes that enhance the resilience to climate change impact on agriculture.

4.2 Gramin Krishi Mausam Sewa (GKMS): Operational Agromet Advisory Services in India

GKMS is one of the flagship schemes of Ministry of Earth Sciences (MOES-IMD). It has been seen that farmers who have access to early-warning systems such as weather forecasting can better cope and adapt to a changing climate. Farmers plan better farming activities, including the choice of crop varieties to plant, after having had access to weather forecast information.

Emerging digital technologies provide an opportunity to use information and communication technology-enhanced extension and climate services that can provide timely information that farmers can use for decision making and adapt their farming practices. These could also improve efficiencies of extension services while also reducing their cost. Climate resiliency at the farm level is essential to achieve food security and improve the livelihoods of rural communities, especially in countries and communities that depend on local agricultural production to ensure household income and achieve daily adequate caloric intake and balanced nutrition.

India Meteorological Department (IMD) under Ministry of Earth Sciences (MoES) started weather services to farmers through 'Farmers Weather Forecast' in the year 1945. Agri-met Advisory Services (AAS) bulletin in the country was started in 1976 and demand for these services has increased gradually. Further, it was enhanced into Multi-institutional Programme and the Integrated Agri-met Advisory Services was started in collaboration with National Centre for Medium-Range Weather Forecasting (NCMRWF) in 2006 for district-level Agri-advisory services through 130 Agri-Meteorological Field Units (AMFUs) covering 683 districts across the country.

IMD, in collaboration with the Indian Council of Agricultural Research (ICAR), State Agricultural Universities and other institutes, is providing information on the weather forecast and crop-specific advisories on agricultural operations at district and block level based on medium and extended range weather forecasts and contributes to forecast based crop/livestock management strategies and operations aimed towards promoting sustainable agriculture and safeguard for livelihood to the farming community.

District-specific medium-term forecast information and advisories help maximize output and avert crop damage or loss. It also helps growers to anticipate and plan for chemical applications, irrigation scheduling, disease, and pest control, and many more weather-related agriculture-specific operations. Such operations include cultivar selection, their dates of sowing/planting/transplanting, dates of intercultural operations, dates of harvesting, and also performing post-harvest operations. Thus, Agri-met advisories help in increasing profits by consistently delivering actionable weather information, analysis, and decision support for farming situations. Agri-met Advisories are being disseminated through the Kisan Portal launched by the Ministry of Agriculture & Farmers' Welfare (MoA&FW), Farmer Awareness programmes (FAP), and other NGOs and private companies under Public-Private Partnership (PPP) model. An Agri-met-DSS web interface has been devised for value addition and verification of District and block level medium range weather forecast by

Meteorological Centers and Regional Meteorological Centers of IMD and automated preparation of AAS bulletins at block and district levels. District Agri-met Units (DAMUs) in the premises of Krishi Vigyan Kendras (KVKs) have been established for running AAS at subdistrict/block level. Real- time weather data is collected online and integrated into Agromet-DSS and other mobile Apps. Robust mechanism for dissemination has been evolved by inducting mobile Apps like Meghdoot, social media Apps (WhatsApp) and also SMS & IVRS using mobile phones. Weather alerts and warning through nowcast (valid for next 3 hours) are shared to farmers through mobile Apps, Farmer awareness Programmes (Fig. 2) and SMS for swift response. These information and advisory resources are also shared with various agencies for use in their data platforms like Kisan Suvidha, Umang, Kisan Mitra, MP Kisan etc., to enhance outreach. Dashboard has been created in the Agromet-DSS and Agrimet Division website (www.imdagrimet.gov.in) for monitoring entire process and follow-up. Real-time dynamic feedback from the farmers is also collected and integrated in Agromet-DSS for course correction.

Figure 2. The farmer awareness programme (FAP) being conducted by District Agro-Met Units (DAMU), under Gramin Krishi Mausam Seva

The findings of an impact study conducted by the National Centre for Applied Economic Research (NCAER) for estimating the economic benefits of advisory service to farmers during April 2018 - March 2019 under the GKMS through the Monsoon mission programme of the Ministry of Earth Sciences are summarized below:

- 98 percent of surveyed farmers made modifications to at least one of the nine critical practices based on the weather advisories. 31 percent of farmers made modifications to all nine critical practices.
- The average annual income of farming households which adopted no modification worked out to be Rs. 1.98 Lakh; Rs. 2.43 Lakh for those who modified 1 to 4 practices; Rs. 2.45 Lakh for those who modified 5 to 8 practices and Rs. 3.02 Lakh for those who adopted all the nine changes.
- 80 percent of the farmers receiving information on high-resolution weather events reported having reduced losses.
- With an estimated annual income gain of Rs. 12,500/- per agricultural household belonging to the Below Poverty Line category in the rain-fed areas, due to the improvement in weather forecasts, the total income gain is estimated at Rs. 13,331 crores (1.83 billion USD) per annum in rain-fed districts.

5. Satellite Remote Sensing for Study of Climate Change vis-à-vis Agro-ecosystems

India has a long tradition of use of satellite data for agricultural applications. Starting from the monitoring of the coconut root wilt in Kerala in 1969 till current operational applications of crop forecasting, drought assessment, crop insurance, etc. the RS applications in agriculture have grown manifold (Navalgund and Ray, 2019; Ray *et al.*, 2019). The report on Doubling Farmers' Income has recommended the use of advanced technology for improving the resilience of farmers to the impact of climate change. One such advanced technology is satellite remote sensing. Satellite remote sensing (RS) refers to the use of reflectance/radiance/emittance data received, in different parts of the electromagnetic spectrum, through sensors onboard earth-orbiting satellites for mapping and monitoring of earth resources. Remote sensing has been very useful for agricultural applications because of the following characteristics of the RS data.

- Synoptic/large area coverage.
- High temporal revisits enabling regular observations.
- Observation capability in multiple spectral domains, such as optical, thermal, and microwave, etc.
- Variable spatial resolution, enabling mapping at different scales, from local to global.
- Availability of long-term satellite data, which helps to study the impact of climate change.
- Data are available in digital format, which enables the application of algorithms and models.
- Many satellite data/products (e.g., NOAA, MODIS, SPOT VGT, INSAT, Landsat, Sentinel 1&2) are available free, which facilitates climate change research.

6. Conclusion

To ensure food and nutrition security in the face of the growing demand for food and increased competition for natural resources and the climate crisis, there is an urgent need to identify suitable opportunities for environmental, economic, and social synergies. The agriculture sector can be looked at as a driver of economic development, based on resilient production with efficient use and management of natural resources. It will also require the promotion of a new generation of food and nutrition policies to address malnutrition in all its forms and provide sustainable, healthier, and more nutritious varieties of food. Sustainable development is a dream of all Governments and international organisations. United Nations Member States adopted seventeen Sustainable Development Goals (SDGs) in 2015 as a universal call of action to end poverty, protect the planet and ensure that all people enjoy peace and prosperity by 2030. Global efforts are synchronizing in form of commitments made by the countries in the framework of the 2030 Agenda, the Sendai Framework for Disaster Risk Reduction, Paris Agreement, and Nationally Determined Contributions (NDCs) to transform agriculture with an integrated and multidisciplinary vision and generating an enabling environment for this purpose.

Agri-ecosystem is a complex system, within which changes are driven by the joint effects of economic, environmental, political, and social forces. It is the sector most vulnerable to climate change due to its high dependence on climate and weather. Global Framework for Climate Services of WMO has identified agriculture and food security as one of five main areas at Global, Regional, National, State, and Local levels, to address implications of climate change. It has been well recognized that climate change and increasing climate variability affect food security in all of its 4 dimensions — availability, accessibility, utilization, and stability. More frequent and intense extreme weather events are already having significant impacts on food production, food distribution infrastructure, livelihood assets, human health, and food emergencies, in both rural and urban areas.

To make life sustainable on the earth, there is a need to adopt alternative energy resources, look for cleaner technologies, work for building resilience in our agricultural ecosystems, enhance adaptations in communities to climate change, look for sustainable management of wastes generated by industrial societies and conserve our traditional knowledge, so that our growth is sustainable. SDGs have been framed for global human development, but the challenges differ regionally. As such, we must learn to tap the local resources and traditional knowledge to address the challenges of sustainable growth. Innovative action plans can be formulated at the local level for education, healthcare, and hygiene by adopting new models suited to the local conditions.

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National Symposium on Digital Farming: The Future of Indian Agriculture
2-3 February 2023, ICAR-IISS, Bhopal

Digital Agriculture and its Role in Soil Health Management

Ashok K. Patra, Nishant K. Sinha, Jitendra Kumar, Dhiraj Kumar and J. Somasundaram

ICAR-Indian Institute of Soil Science, Nabibagh, Berasia Road, Bhopal-462038, Madhya Pradesh

ABSTRACT

Digital agriculture is the use of technology to improve the efficiency, productivity, and sustainability of agricultural practices. With the increasing use of data and digital tools such as sensors, drones, and precision planting and harvesting equipment, farmers can better understand the growth of their crops and soil conditions, which can help optimize planting and harvesting times and reduce the environmental impact. Precision irrigation, nutrient management systems, and software and digital tools are also being developed to support digital agriculture further.Although soils are generally heterogeneous, digital technology such as remote sensors, drones, precision irrigation systems, GPS-guided machinery, data analytics, robotics, artificial intelligence, and machine learning will be helpful in managing soil variability in order to ensure sustainable resource management. Overall, digital agriculture can help farmers to improve the efficiency, productivity, and sustainability of their operations, while also addressing some of the major challenges facing the agricultural industry today.

Keywords: Digital Technology, Sensor, Precision agriculture, Artificial intelligence

Introduction

Agriculture is one of the significantcontributorsto India's economy, with an 18% gross domestic product (GDP) and involving about 57% of people in rural areas. Over the years, although India'stotal agronomic output has increased, but the number of growers has fallen from 71.9% in 1951 to 45.1% in 2011. It has been estimated that total workforce in agriculture will drop to 25.7% in 2050 (Economic Survey, 2018). In rural areas, farming familiesgradually lose the next generation of farmers, overwhelmed by higher costs of cultivation,low per capita productivity, poor soil health, and migrations to a non-farmingor higher remunerative occupation. Presently, the world is on the verge of a digitalrevolution, and so it is the appropriate time to connect the agricultural landform with wireless technology to introduce and accommodate digital connectivity with farmers (Dhanaraju *et al.,* 2022). The high demand for information and communication technology (ICT) in agriculture applications has led to the concept of smart farming. In this respect, moving from the main features of the Fourth Industrial Revolution (Industry 4.0) promoted by the European Community, new approaches have been suggested and adopted in agriculture, giving rise to the so-called Agriculture 4.0 (Gagliardi *et al.,* 2022). Agriculture 4.0 evolved from Agriculture 1.0 (Fig. 1.), which refers to the traditional agricultural era,mainly relying on manpower and animal forces.In this stage,though simple tools like sickles and shovels were used in agriculturalactivities, humans still could not get rid of heavy manual labor, so productivityremained at a low level. Until the 19th century, steam engineswere improved and widely used to provide new powers in all walks oflife and industries, including agriculture. It came to the era of Agriculture 2.0 when various agricultural

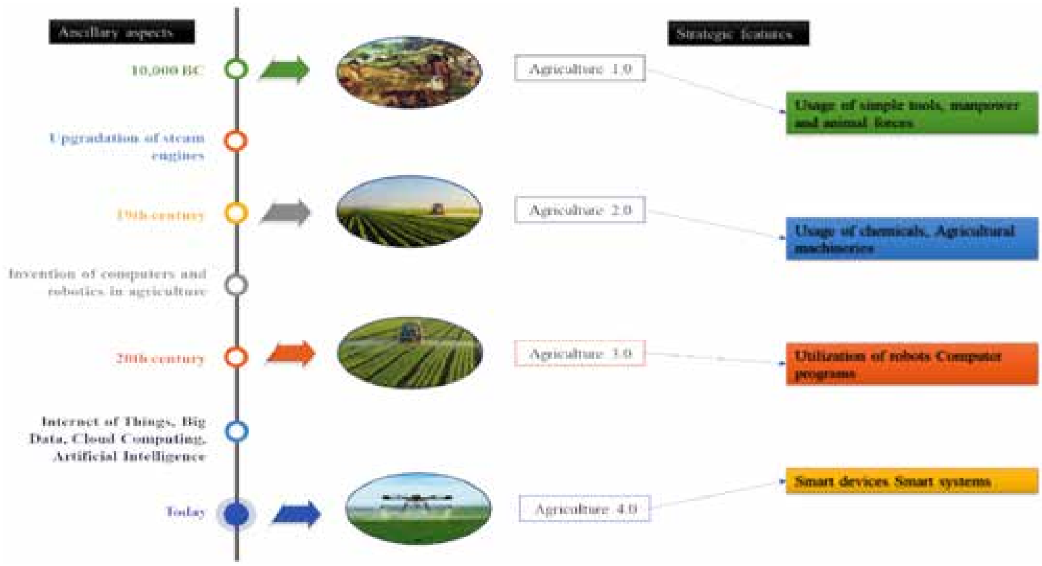

Figure 1. The development process from Agriculture 1.0 to Agriculture 4.0. (Adapted from Dhanaraju *et al.* **2022)**

machinery were operated byfarmers manually, and plenty of chemicals were used. Agriculture 2.0 significantly increased the efficiency and productivityof farm work.Nevertheless, this substantial improvement brought tooharmful consequences: field chemical contaminations, destruction ofthe ecological environment, excessive consumption of powers, andwaste of natural resources. In the 20th century, Agriculture 3.0 emerged from the rapid development of computing and electronics.Computer programs and robotic techniques allowed agricultural machineryto perform operations efficiently and intelligently. Before theproblems left in Agriculture 2.0 went too far, strategies were adjusted inAgriculture 3.0. The reasonable work distribution to agricultural machineryreduced the use of chemicals, improved the precision of irrigationand so on. Nowadays, the evolution of agriculture steps intoAgriculture 4.0, thanks to the employment of current technologies likethe Internet of Things, Big Data, Artificial Intelligence, Cloud Computing,Remote Sensing, etc. These technologies' applications can significantly improve agricultural activities' efficiency (Zhai *et al.,* 2020).

Digital agriculture, also known as smart farming, refers to the use of technology to improve the efficiency, productivity, and sustainability of agricultural practices. It includes using data and digital tools such as sensors, drones, and precision planting and harvesting equipment to collect information about crop growth and soil conditions, as well as the use of precision irrigation and nutrient management systems.One of the key benefits of digital agriculture is the ability to gather and analyze large amounts of data about crop growth and soil conditions (Sinha *et al.,* 2018). This information can be used to optimize planting and harvesting times and identify areas of the field that may require more attention or resources. By using precision planting and harvesting equipment, farmers can also reduce the amount of seed, water, and fertilizer used, which can help lower costs and reduce environmental impact. Another important aspect of digital agriculture is precision irrigation and nutrient management systems (Sinha *et al.,* 2019). These systems use sensors to monitor soil moisture and nutrient levels and automatically adjust irrigation and fertilization systems to ensure optimal growth conditions for crops. This can help to reduce water usage and improve crop yields while also reducing the risk of nutrient runoff and other environmental impacts.

Drones and other aerial technologies also play an increasingly important role in digital agriculture. Drones can be used to gather data on crop growth and soil conditions, as well as to map fields and identify areas that may require more attention or resources. They can also spray pesticides and fertilizers, which can help reduce labor costs and improve the efficiency of these processes (Rani *et al.,* 2019). In addition to these technologies, several software and digital tools are being developed to support digital agriculture. These include precision planting and harvesting software and precision irrigation and nutrient management systems. These tools can help farmers to optimize their crop yields and reduce costs, while also improving the sustainability of their operations

Need for digital agriculture

The need for digital agriculture arises from several factors, including:

1. **Population growth:** The global population is projected to reach almost 10 billion by 2050, and food production will need to increase by 70% to meet the demand. Digital agriculture can help to increase crop yields and improve efficiency in food production.
2. **Climate change:** Climate change affects global weather patterns, which can significantly impact crop yields. Digital agriculture can help farmers to adapt to these changes by providing data and tools to optimize planting and harvesting times, and to identify areas of the field that may be more vulnerable to weather changes.
3. **Resource constraints:** Agriculture is a major consumer of water and other resources, and there is a growing need to improve efficiency and reduce waste. Digital agriculture can help to optimize water usage, reduce fertilizer and pesticide inputs, and improve resource management.
4. **Labor shortages:** The agricultural workforce is aging and there is a shortage of young people entering the industry. Digital agriculture can help to automate many tasks, reducing the need for manual labor.
5. **Increased competition:** The global market for food is becoming increasingly competitive, and farmers need to find ways to increase efficiency and reduce costs. Digital agriculture can help farmers to optimize crop yields, reduce costs, and improve the competitiveness of their operations.

Therefore, agriculture needs to become more environmentally, economically, and socially sustainable through technology, digital, and innovation to assure food security for future generations. To ensure sustainable resource management, agriculture can entail the use of technology like remote sensors, drones, precision irrigation systems, and GPS-guided machinery as well as data analytics, robotics, artificial intelligence, and machine learning. These digital agricultural technologies can be utilized to gather information on agriculture that will help in increased agricultural efficiency, reduced costs, improved crop yields, and reduced environmental impact. It also helps farmers make more informed decisions about soil, crop management, and resource allocation and minimizing waste.Implementing digital solution can provide reliable management and monitoring of soil and crops. Farmers can get a complete digital analysis of farms in real-time and they can act accordingly and don't have to apply excess pesticides, fertilizers and reduce overall water consumption. The other benefits of digital agriculture are shown in Fig. 2.

Soil fertility management through digital technology

Increasing crop productivity to meet the future demand of the burgeoning population will increase both soil nutrient removal and the importance of replenishing soil fertility through efficient

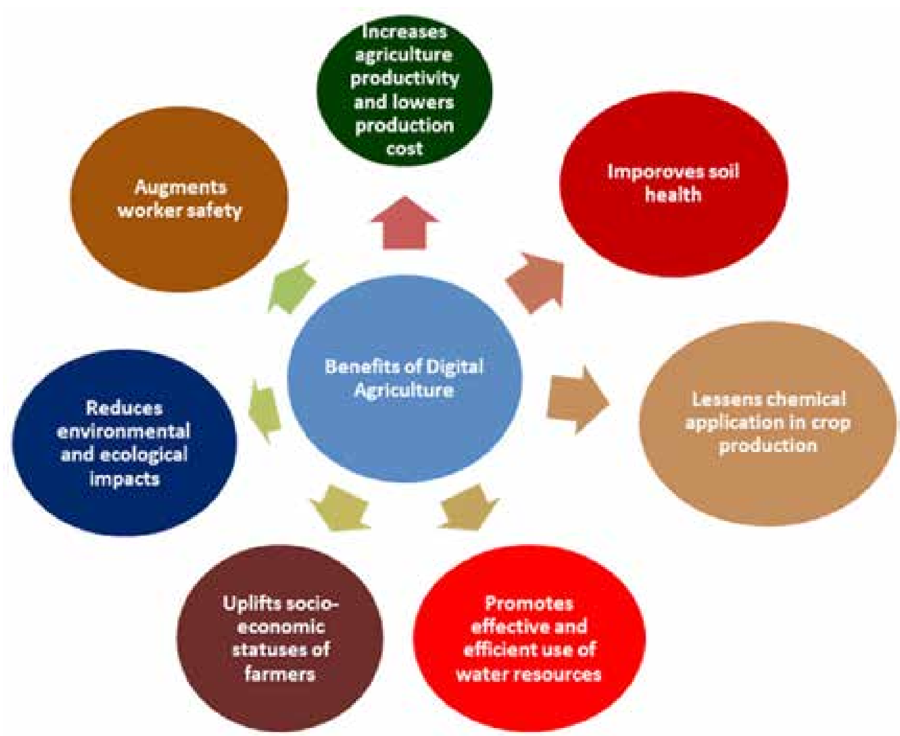

Figure 2. Benefits of digital agriculture

nutrient management practices. Improving nutrient-use efficiency in production agriculture requires improved estimates of plant-available nutrients in the root zone, enhanced crop response to applied nutrients, and reduced offsite nutrient transport (Havlin and Heiniger, 2020). Soil is heterogenous, and its physical, chemical, and biological show greater spatial and temporal variations. Therefore, the soil needs differential input, such as fertilizer, water etc., for better management. For example, the usual, uniform fertilization of the fields can lead to partial over-or under dosing. Overdosing can lead to exposure of surface and groundwater. Underdosing can result in an under-supply of nutrients and thus losses in yield and quality at the site.Digital technology provides an opportunity to manage these variations efficiently. Digital technology can be used in various ways to help manage soil fertility and enhance nutrient use efficiency. For example, precision agriculture techniques such as precision fertilization, precision irrigation, and precision planting can optimize crop yields while minimizing the use of resources such as water and fertilizer. Additionally, digital tools such as remote sensing, geographic GIS, and precision farming software can collect and analyze soil properties and crop growth data, which can be used to make data-driven decisions about fertilization and other management practices. Overall, digital technology can help farmers to improve the efficiency and sustainability of their soil fertility management practices. There are various tools and techniques are available to implement digital technology in agriculture for better utilization of resources and enhanced productivity (Fig. 3). Some of these tools and techniques are discussed below in the context of soil fertility management.

(1) Remote sensing

Remote sensing is a technology that can gather information about soil fertility from a distance. It can be done using a variety of sensors, such as multispectral and hyperspectral sensors, which can be mounted on aircraft, drones, or satellites. These sensors can be used to measure the reflectance of

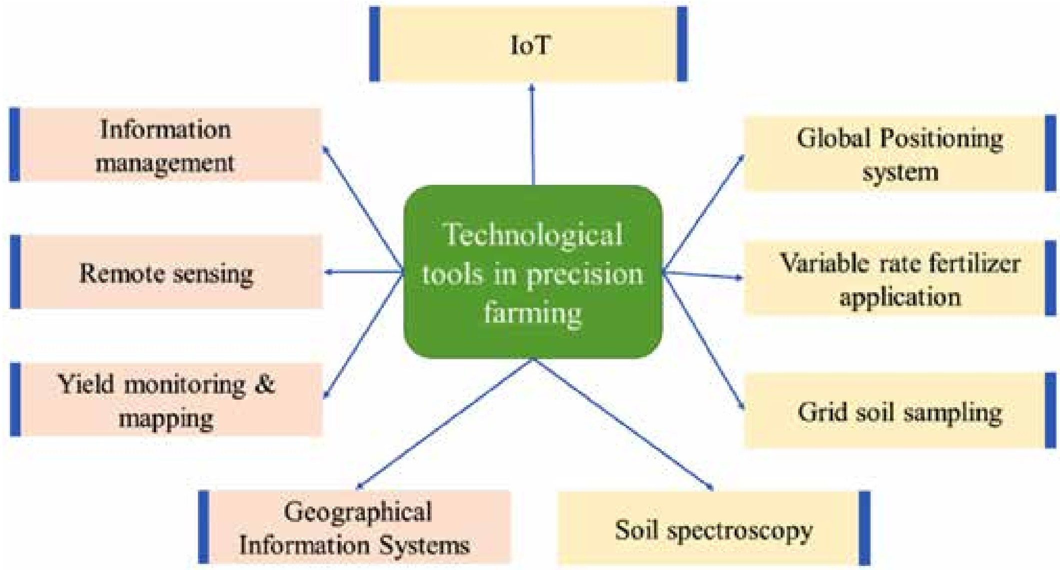

Figure 3. Tools and techniques for implementation of digital agriculture

different light wavelengths, which can infer information about soil properties such as nutrient content, organic matter, pH, and soil moisture. Additionally, remote sensing can monitor crop growth and health, providing valuable information about the need for fertilization or other soil management practices. For example, NDVI (Normalized Difference Vegetation Index) can be used to map vegetation health and growth, while NDWI (Normalized Difference Water Index) can map soil moisture.

The main application of RS in soil fertility is primarily in the spatial assessment of soil fertility in terms of nutrient deficiency represented by poor crop growth & in the preparation of soil fertility maps. The components of soil fertility that can be addressed with RS include organic carbon, NPK, and micronutrient (Fe, Mn, Zn, Cu) levels (Wadodkar *et al.,* 2014). Amongst plant nutrients, nitrogen is one of the most important factors in maximizing crop yields and economic returns to farmers. The spatial variation in nitrogen content has been addressed using crop vigor as a proxy indicator, and spatial interpolation of soil analytical data using RS data as a guiding force for interpolation (Ravisankar and Sreenivas, 2011). In general, Nitrogen deficiency causes a decrease in leaf chlorophyll concentration, leading to an increase in leaf reflectance in the visible spectral region (400-700 nm). However, several other stresses (pest and diseases) may also increase plant reflectance due to reducedchlorophyll (Carter and Knapp, 2001). Diagnosing a specific nutrient deficiency with remote sensing data can be difficult when plants are subjected to deficiencies of multiple elements. Hyperspectral remote sensing was found to be an important tool for diagnosing plant nutrient stress, which is an indicator of soil fertility. Osborne *et al.* (2002) showed the utility of hyperspectral data in distinguishing differences in nitrogen and phosphorus at the leaf and canopy levels. However, the relationships were not consistent with overall plant growth stages.

(2) Sensors

Soil sensors have become smaller, more rugged, faster, more accurate, more energy-efficient,wireless, and more intelligent (ViscarraRossel *et al.,* 2010; Zerger *et al.*, 2010). They can be single hand-held devices or mounted on vehicles for mobile (Adamchuk *et al.,* 2004) or autonomous operation (e.g., Manderson and Hunt, 2013) using solar energy/battery. Sensors can use various technologies and frequencies across the electromagnetic spectrum. They can also be mechanical, electro-chemical, and biological. Many are available commercially, and some are under development (Viscarra Rossel *et al.,* 2011).There is great interest in soil sensing with visible–near (VIS, NIR) and mid-infrared (MIR) spectrometers because their spectra can characterize the respective chemical, physical, and mineralogical composition of the soil. Large databases of soil spectra are being developed to help meet the growing demand for soil information to assess and monitor soil at a range of scales (Viscarra Rossel *et al.,* 2016). Soil visible–infrared sensing is analternative to laboratory analyses of soil attributes such as organicand inorganic carbon, pH, total nitrogen and phosphorus, water, texture, and mineralogy (Nocita *et al.,* 2015), because the processing of the sample, if required, is simple, measurements are reproducible and results can be obtained at a much cheaper cost. The measurements can be made on wet soil that is *in situ* under field conditions, removing the need for sample drying, grinding, and other preparations (Ji *et al.,* 2015; Minasny *et al.,* 2011).

Besides this, a promising method, which is potentially well suited for the 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. Furthermore, in comparison to X-ray fluorescence (XRF), the whole range of elements, including the light elements like N, is measurable by LIBS. Thus, LIBS appear particularly well suited for the high-density soil analysis of agricultural fields on a spatial scale (Erler *et al.,* 2020).

Further, spectrometers are becoming cheaper, smaller, and more accessible. Currently, new technologies that use micro-electro-mechanical structures (MEMSs) (Johnson 2015), thin-film filters, lasers, light-emitting diodes (LED), fibre optic assemblies, and high-performance detector arrays (Coates, 2014) are being used to produce miniaturized hand-held instruments that are rugged and cheap. They are also now being incorporated into mobile telephones.The X-ray spectrometer has also been widely used for the measurement of the total elemental composition of soil macro and micronutrients, soil hydraulic properties (Rab *et al.,* 2014), soil compaction (Keller *et al.,* 2013) and soil consolidation (Keller *et al.,* 2013; Ma *et al.,* 2015; Pires *et al.,* 2014). Périard *et al.* (2016) reviewed the use of X-ray for monitoring time-dependent changes in soil properties such as bulk density, tortuosity, porosity, pore network characteristics, permeability, volumetric water content, solute

Table 1. Sensor types and their uses

S. No.	Sensor type	Example applications	References
1.	Electro-chemical	Soil pH, nitrate, potassium	Adamchuk *et al*. (2007; 2004)
2.	Electrical and electromagnetic	Soil texture (sand, silt, clay), soil moisture content, cation exchange capacity	Kim *et al*. (2009); King *et al.* (2005); Sudduth *et al*. (2003)
3.	Optical and radiometric (spectral based)	Soil organic matter,pH, soil texture, Av-P, Av-K and heavy metals	Rossel *et al*. (2006); Chang *et al*. (2001), Kuang *et al.* (2012)
4.	Acoustic	Soil texture (sand, silt, clay), soil bulk density	Grift *et al*. (2002)
5.	Mechanical	Soil compaction, compacted soil layers	Manor and Clark (2001)
6.	Laser based and X-ray spectroscopy	Elemental analysis of soil	Erler *et al.* (2020)

transport parameters, fractal properties, soil aggregate characteristics, unsaturated hydraulic conductivity, and soil water retention curves. Besides this, rapid and non-destructive quantification of spatially-variable soil nutrients can be made possible with on-the-go or hand-held sensors using optical or electromagnetic sensors.Table 1 summarises the classification of different sensors and their uses in determining soil variables.

(3) Soil spectroscopy

Soil spectroscopy or dry chemistry is an evolving technology for rapid, cost-effective and non-destructive characterization of soil properties based on the interaction of electromagnetic energy with matter (Nocita *et al.,* 2015). Here, electromagnetic spectra of soils are correlated with the conventional laboratory-measured soil properties of interest to develop mathematical prediction models. After the satisfactory validation of the prediction models with the independent dataset, these prediction models are used for quantitative soil prediction. This technique opens up new vistas for its application in SSNM, monitoring soil quality in landscapes, and digital soil mapping. One of the advantages of soil spectroscopy is that it simultaneously retrieves various soil properties from a single spectrum. However, the accuracy of the spectroscopic technique depends on the accuracy of the conventional laboratory methods used to analyse different soil properties and the multivariate statistical procedures followed for the development of prediction models. These methods can be used to estimate numerous soil attributes, including minerals, organic compounds and water (Table 2).

Table 2. Different wavelength and their uses in agriculture/ soil research

S. No.	EMR region	Wavelength range	Use in soil research	References
1.	Gamma ray	<1 nm	Soil texture, EC, pH, total organic carbon and total nitrogen	Mahmood *et al*. (2012)
2.	X-ray	1-10 nm	Heavy metal, soil texture, pH, cation exchange capacity	Zhu *et al*. (2011) Sharma *et al*. (2015)
3	UV	10-400 nm	Organic carbon	Schomakers *et al*. (2014)
4.	Visible-Near infrared	400-2500 nm	All soil properties	Feyziyev *et al*. (2016), Paz-Kagan *et al*. (2014), Nocita *et al*. (2015)
5.	MIR	2.5 -50 μm	All soil properties	Waruru *et al*. (2015), Towett *et al*. (2015)
6.	Microwave	0.1 to 100 cm	Soil moisture	Mohan *et al*. (2015), Das and Paul (2015)

The indisputable advantages of spectroscopic methods for studying soils in comparison with routine laboratory chemical methods are:

- Speed
- Low cost of analysis
- Minimum environmental hazard
- Minimum risk to human health

- No need to purchase chemicals and utensils
- Possibility of non-destructive method of soil analysis (soil surface survey)
- Equipment portability

Nevertheless, there are a number of limitations to introduce spectroscopic methods:

- A reliable regional calibration data has to be collected in addition to existing global spectral libraries or soil libraries from other countries and regions. More the calibration data, the higher the accuracy of measurements for different soil properties, i.e. the latter is constantly growing.
- For more accurate results drying and grinding of soil samples are required, which slows down the analysis speed.

(4) Internet of things

IoT (Internet of Things) technology can be used in soil fertility management by connecting various sensors and devices to collect data on soil conditions such as moisture, pH, temperature, and nutrient levels. This data can be analyzed to determine the best times for planting, fertilizing, and watering crops. IoT-enabled devices such as precision irrigation systems and fertilizer applicators can also be controlled remotely to optimize crop growth and reduce waste. It can lead to more efficient use of resources and higher crop yields. A block diagram for IoT based nutrient system is presented in Fig. 4.

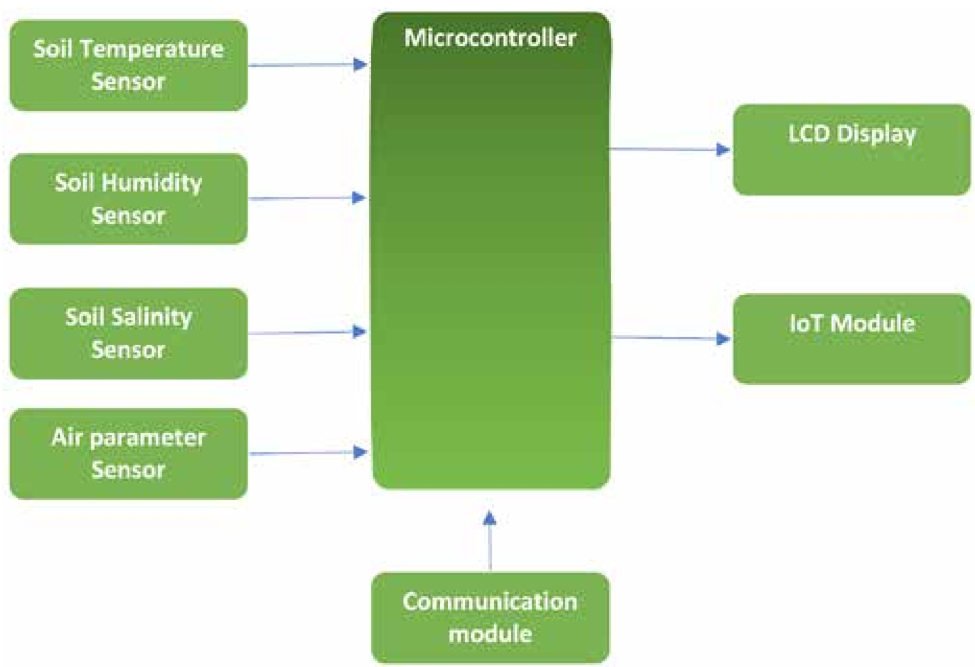

Figure 4. Block diagram of IoT-based nutrient management system

IoT can also be used to track soil erosion and monitor changes in land use, which can help scientists understand how different management practices affect soil health over time. It can lead to the development of more sustainable farming practices. Overall, IoT technology can be a powerful tool for soil scientists to better understand and manage soil resources and help farmers to improve their crop yields and reduce environmental impact.

Summary

Digital agriculture plays a crucial role in modern agriculture by allowing real-time monitoring of several soil properties. Digital agriculture uses many sensors to monitor soil conditions, including (a) moisture sensors: These sensors can measure the water content of soil, which is an essential factor in crop growth and water management, (b) pH sensors: These sensors that measure the acidity or alkalinity of soil, which can affect nutrient availability and crop growth. (c) Temperature sensors: These sensors measure the temperature of soil, which can affect microbial activity and crop growth. (d) Nutrient sensors: These sensors can measure the levels of various nutrients such as nitrogen, phosphorus, and potassium in soil. This information can be used to optimize fertilizer application and improve crop yields. (e) Carbon and microbial sensors: These sensors can measure carbon and microbial activity in the soil, allowing for a better understanding of soil health and how it is affected by different management practices. (f) Other sensors: There are also sensors that can measure other soil properties such as electrical conductivity, radiation, and salinity. Sensor data can be transmitted wirelessly and analyzed using data analytics and machine learning algorithms, which can help to optimize crop growth and improve soil health. Additionally, sensor networks can be used to monitor soil erosion, changes in land use and track soil health over time.

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National Symposium on Digital Farming: The Future of Indian Agriculture
2-3 February 2023, ICAR-IISS, Bhopal

Technologies for Automation of Weed Control in Conservation Agriculture

T.K. Das*, Priyanka Saha, Arkaprava Roy and Rishi Raj

Division of Agronomy, ICAR-Indian Agricultural Research Institute, New Delhi-110 012

**Email: tkdas64@gmail.com*

ABSTRACT

Conservation agriculture (CA) is a concept of integrated management of crop, soil, water, and other agricultural resources/ inputs towards achieving the objective of economically, ecologically and socially sustainable agricultural production. It advocates a paradigm shift from conventional agriculture. The CA principles have tremendous effects on weed seed bank, and their spread and dynamics. Usually, weeds cause crop yield loss by 33%, pathogens by 26%, insects by 20%, storage pests by 7%, rodents by 6%, and others by 8%. In India, total economic losses due to weeds in 10 major field crops in 18 states were estimated to be nearly 11 billion USD annually. Highest loss was in rice (USD 4420 million) followed by in wheat (USD 3376 million) and soybean (USD 1559 million). Therefore, economically viable, technologically feasible, and environmentally sustainable weed management in CA is the need of hour for successful crop production. Under shrinking availability of labourers, manual weeding using small implements /hand tools is hardly practicable/ advisable. In large scale crop production, labour-intensive weeding is usually not economical and even not feasible due to high labour cost and/or insufficient availability of labourers. There is a need to develop labor-saving weed control technologies under CA. The precision weed management (PWM) utilizing automation technologies is the new paradigm for weed control in crops, which could be an important tool for integrated weed management approach. Automation technologies that include tools and methods and do not require more human force are, therefore, thought to be more suited to CA. Automation weed control technologies that include spot flaming, electromagnetic irradiation, steam/ hot water application, robotics, drone, machine vision technology with data processors and automated device, and mechanical automated sprayers can be adequately tested and then adopted for automation weed control in conservation agriculture.

Key words: Automation, Laser weeding, Robovator, Robocrop

1. Introduction

Conservation agriculture is a concept for resource-saving agricultural crop production that strives to achieve acceptable profits together with high and sustained production levels while concurrently conserving the environment. It can enhance natural and biological processes above and below the ground. It involves a paradigm shift in crop production from conventional agriculture. CA is believed to have potential to achieve acceptable profits, high and sustained production levels, and conservation of the environment. CA is based on the practical application of three interlinked principles: continuous zero or minimum mechanical soil disturbance by direct planting, permanent vegetative soil cover or mulch to protect the soil surface, and diversification of cropping systems including legumes. These principles have tremendous effects on weed seed bank enrichment, weed spread and dynamics. Weeds cause higher reduction in crop yield than other pests and diseases although they remain underestimated in tropical agriculture. Highest loss is caused by weeds (33%), followed by pathogens (26%), insects (20%), storage pests (7%), rodents (6%), and others (8%) (Anonymous, 2021). In India, total economic losses due to weeds in 10 major field crops in 18 states are ~11 billion USD annually (Gharde *et al.,* 2018). Actual economic losses were high in the case of rice (USD 4420 million) followed by wheat (USD 3376 million) and soybean (USD 1559 million). Therefore, weed control is highly necessary for successful crop production. Traditional weed control using hand hoes to scrape the soil surface to remove weeds is inter alia suggested for smallholder farmers with an abundant labour force. In largescale arable crop productions, labour-intensive weeding is usually not viable due to high labour costs and/or insufficient labour force availability. Traditional implements for within-crop mechanical weed control such as cultivators, hoes or harrows (pulled by a tractor) are inefficient and impractical when large quantities of plant residues are present. Other tools potentially suitable for mechanical weed control with high residues, such as rotary hoes or cultivators, are generally not efficient enough. Automation technologies, that is tools and methods which do not require more man force, are therefore thought to be more suited to CA. Automation weed control technologies, including spot-flaming, electromagnetic irradiation, steam/ hot water application, robotics, drone application and mechanical automated sprayers are upcoming technologies with regard to their suitability for CA.

2. Weed dynamics under CA

CA changes the crop microclimate that leads to a paradigm shift in weed germination and emergence. Some weeds are favoured by the changes in microclimate and emerge profusely than others under continuous ZT system. This results in weed shift, particularly towards perennials under CA systems, which are better adopted under less-disturbed soils. Also, herbicides are not effective against most perennial weeds, which reproduce, mainly, through vegetative means. Perennial monocots like *Cyperus rotundus* (Purple nutsedge), *Saccharum spontaneum* (Tiger grass), *Cynodon dactylon* (Bermuda grass) and *Sorghum halepense* (Johnson grass) reproduce from underground vegetative structures, tubers, rhizomes, stolon, corms etc. *Euphorbia microphylla* after wheat harvest also became dominant in CA-based rice-wheat system. Perennial dicots weeds such as *Polygonum plebejum* (Indian knotweed) and *Alternanthera philoxeroides* (Alligator weed) have been observed in continuously CA plots under rice-wheat system, and *Sonchus arvensis* (Sow thistle) under CA-based rice-mustard system. Annual weed shifts towards small-seeded ones is generally observed under CA. But, *Phalaris minor* although has small seeds, is reduced gradually under ZT compared to CT system in the Indo-Gangetic Plains (IGPs). This may be attributed to: (i) higher soil strength in ZT because of crust development in the absence of tillage, which can impede seedling emergence, (ii) less soil temperature fluctuation under ZT, and (iii) relatively lower levels of light stimuli, N mineralization and gas exchange under ZT.

3. Weed management 5R Stewardship

Weed management is a science as well as an art. The chemistry of herbicide and the art of application of herbicide play role on the overall efficacy that can be achieved due to herbicide application. Like "4R Stewardship" in nutrients management, the "5R Stewardship" should be followed for higher weed control efficacy with no phytotoxicity to crops and no/less implications to environment. These are:

i) **Right choice of herbicide:** herbicide should be selected based on the spectrum of prevalent weed to be controlled, time of application, and crop selectivity.

ii) **Right source of herbicide:** herbicide should be procured from authentic sources/companies for ensuring that the required active ingredient labeled is present and the herbicide is within the expiry date.

iii) **Right dose of herbicide:** herbicides should be applied at the doses recommended for crops considering the time of application, crop selectivity and soil conditions.

iv) **Right time of application of herbicide:** herbicide should be applied at appropriate time, pre-planting, pre-emergence or post-emergence, and the weed emergence and their growth stages should be considered upon post-emergence applications.

v) **Right method of application of herbicide:** Herbicides should always be applied by using a sprayer, preferably a knapsack sprayer with flat fan or flood jet nozzle, proper pressure for delivery of spray droplets, and proper volume rate of water.

4. Weed Management New Paradigm

Managing weeds has always been placed at the center of agricultural activity by farmers since ancient times. The control of weeds is a big challenge in agriculture and in many cases a complex, controversial and also expensive problem to solve. In fact, weed management accounts for nearly one third of the total cost of the production of field crops. Currently, weed management in agricultural systems branches out into two distinct directions corresponding to different approaches. On the one hand is the widespread use of synthetic herbicides, while on the other, weed control is widely based on mechanical, cultural and physical methods. Mechanical methods are generally less efficient, while herbicides have a negative impact on the ecosystem. Thus, weed management requires an integrated approach that minimizes the drawbacks of mechanical and chemical weed control. Indeed, there is a great need for a new weed management paradigm in modern agriculture that is based on automation and artificial intelligence technologies. Several methods are being developed to observe and detect weeds so that control measures can be applied wherever and whenever they are needed. This paradigm shift is based on an interdisciplinary work to harness powerful technology tools and use them to control weeds. From this perspective, the precision weed management (PWM) utilizing automation technologies contributions to weed control, which could be considered to be an important upgrade in IWM.

5. Precision Weed Management (PWM)

Smart farming technologies, such as smart sensors, remote sensing, air vehicles, satellites, Internet of Things (IoT) technology etc. are becoming increasingly common in modern agriculture to assist in optimizing agricultural production and minimizing the wastes and costs. Precision farming or site-specific crop management is a concept based on sensing or observing and responding with management actions to spatial and temporal variability in crops. The “sensing” component of the concept is a fundamental element of precision farming, as is variable rate technology (VRT), which offers an effective way to protect the environment and increase economic benefits. This technology works by integrating a variable rate control system with a sprayer for fertilizer, pesticide or herbicide applications. The application at a varied rate can be fundamentally based on maps or sensors. Indeed, there are two main methods for implementing site-specific variable rate applications (VRA): map-based VRA, which adjusts the application rate of a crop production input based on the information contained in a digital map of field properties, and sensor-based systems that use data from real-time sensors to match inputs to the needs of the soil and crop. From this perspective, precision farming technologies can provide many benefits for weed management practices. A wide range of weed sensing techniques have been studied since the beginning of the century. With large areas, the most cost-effective approach may be remote sensing to provide a farm, or a large area encompassing several farms, with maps of weed occurrence. Remote sensing uses satellite or manned/unmanned aerial vehicles to collect data. Unmanned aerial vehicles (UAVs) can be highly valuable, since they allow for site specific weed management (SSWM), an improved weed management approach for the highly efficient and environmentally safe control of weed populations, enabling precise and continuous monitoring and mapping of weed infestation. The combination of UAVs with advanced cameras and sensors, able to discern specific weeds, and global navigation satellite system (GNSS) or global positioning system (GPS) technologies, which provide geographical information for field mapping, can help in precisely monitoring large areas in a few minutes. Automation technologies and mechatronics are likely to become more effective and commercially viable as future weed control strategies and they are already being used in industrialized countries with specific crops. Typically, vegetable crops, such as broccoli, cabbage, field-grown flowers, herbs, lettuce, onion and tomato, among others, are hand weeded to achieve intra-row weed control. In this sense, the industry has responded to the need for automation of intra-row cultivators as a viable alternative to hand weeding. Interest in automation of weed sprayers has been rising in recent decades. Precision spraying is able to minimize the amount of herbicide needed on a given crop, compared with traditional broadcast sprayers that usually treat the entire field to control weed populations, which potentially results in unnecessary application to areas that do not require treatment. The application of herbicide in a specific location, i.e., where weeds occur, could reduce costs, the risk of crop damage and excess pesticide residue, as well as potentially reducing the environmental impact. The effectiveness of precision spray systems is based on high levels of crop/ weed differentiation, accurate spray prescription maps, the knowledge of the sprayer tip location relative to the target weed location, accurate herbicide placement and control of the spray drift. For example, spot spraying systems provide potential savings with herbicide use, which can range from 5% to nearly 90% (Berge *et al.,* 2012) depending mainly on the spatial and temporal distribution of weeds found in the treated fields. In addition, according to Jensen *et al.*, the detailed and resource-efficient approach of herbicide spraying with SSWM in smart farming can decrease herbicide consumption by 40% to 60%.

i) Automated Weeders

Split hoe

In Germany, split-hoe is used to manage weeds in the inter-row area of herbaceous, horticultural, and greenhouse plants (Pannacci and Tei, 2014). Split-hoe has the benefits of a hoe, a rotary tilling cultivator, and a brush weeder but none of their drawbacks. A split hoe can be used to uproot weeds that are present in the inter-row area between 0.4 and 0.5 metres and 0.2 and 0.25 metres. The agricultural plants can be covered with a shield. 80 mm of soil are left uncultivated as a result. The horizontal axis with gangs of spike-wheels attached on it, powered by the tractor PTO (Power take off), is used for weeding.

Brush Weeder

A brush weeder that was manually operated and had flexible brushes composed of fibreglass or nylon that rotated around vertical or horizontal axes (Melander, 1998). In addition to burying and destroying weeds, this weeder has the ability to uproot them. To prevent harm to the crop, a guard was put in place as protection. It was recommended for an operator to manually direct the brushes to remove weeds that were nearest to crop plants without harming them.

Finger weeder

A finger weeder consists of two discs that can be tilted with respect to the soil's surface and have peripheral fingers. The fingers may be made of plastic (soft-finger) or rubber-coated iron (hard fingers). The crop row weeds are uprooted and lifted out by the finger weeders. While large finger weeders need a minimum row space of 35 cm, little finger weeders can get away with a minimum row space of 25 cm. On light to medium-heavy clay soils, finger weeders work effectively; however, too-hard soils are not a good fit. The working speed can be between 4 and 12 km per hour. For heavy clay soils, harder fingers are preferred, while for light soils, gentler fingers. However, it works poorly in soils that are incrusted or compacted or when there is long-stemmed residue present (Van der Weide *et al.,* 2008).

Torsion weeder

Torsion weeders have two spring tines per row that point into the crop from either side of the row but beneath the crop leaves. Weeds are shallowly uprooted by weeders. The working speed can be between 4 and 12 km per hour. There should be a minimum of 25 cm between rows. When using torsion weeders, working at faster speeds leads to superior weed control with no yield loss when compared to working at a lower speed. Torsion weeders can only effectively control small weeds.

ECO weeder

An ECO-weeder is a piece of mechanical intra-row weeding equipment that attaches to a tractor with a three-point hitch. The tractor Power take-off (PTO) provides power for the weeding unit. Compared to hand weeding, the ECO-weeder might cut weeding costs by up to 60%.

ii) Thermal weed management

Weeds can be quickly controlled thermally without leaving chemical residues in the soil or water by using fire, burning, hot water, steam, and freezing. Additionally, unlike cultivation methods, which disturb the soil and expose buried seeds to the air, thermal methods are selective towards weeds and do not do so.

Burning

When seed production has already started, fire can be used to kill some of the seeds. The maturity and position of the weed seeds, together with the duration and intensity of the heat produced, all affect how well the weeds are burned. Compared to green seeds, which have a high moisture content, mature and dried seeds are more heat resistant. Even if the majority of seeds still present in plant heads will be killed by strong heat, burning surface residue will only significantly reduce small amount of seeds on or below the soil's surface. When weeds are burned over a large area, valuable surface residue that would typically decompose or be cultivated back into the soil is destroyed (Sharma *et al.,* 2014)

Flaming

The thermal technique known as flaming is the one used most frequently in both conventional and organic farming systems. It uses propane gas burners or, more recently, renewable alternatives like hydrogen to produce combustion temperatures of up to 1900 °C, which quickly raises the temperature of the exposed plant tissues. Plant membranes are damaged by heat, which leads in the loss of cell function. The plants eventually perish or deteriorate significantly (Fennimore *et al.,* 2016).

Compared to mature plants and grass species, dicotyledonous and young weed plants are more susceptible. Flaming has been demonstrated to be less successful at controlling grassy and prostrate weeds and to be most effective at early-stage erect and broad-leaved weed removal (Mia *et al.,* 2020). For weed management in cotton, maize, sorghum soybeans, potatoes and other crops, flaming has been a common practice in the United States since the 1960s.

Freezing

Flame weeding was contrasted with the use of very low temperatures to control weeds (Fergedal, 1993). Liquid nitrogen and carbon dioxide snow, two distinct media, were used for the freezing treatments (dry ice). These were administered by tractor utilizing a straightforward test setup to the newly emerging weeds. The dose-response graphs demonstrated that fire was more effective at killing weeds than either solid carbon dioxide or liquid nitrogen. Only in situations when there was a clear fire risk from igniting would freezing be advantageous.

Steaming

Field-use mobile steaming equipment is now commercially available. The majority of weed seeds in the top 10 cm of soil will be killed by field steaming (White *et al.,* 2000). Field steam sterilization, however, is now prohibited by UK organic regulations. Additionally, it is feasible to eliminate newly emerged weeds using directed steam jets, and equipment suited for use in recreational areas has been developed.

Hot water

When thermal energy is given to plants through the use of liquid or gaseous water (steam), the temperature will soon rise, causing harm to the cellular structure (Rask *et al.,* 2013).

iii) Microwave and Laser Weeding

Microwave radiation

Intense electromagnetic radiation from lamps can also kill weeds or stop them from growing. lasers, microwave magnetrons, infrared radiators powered by propane, or focused sunshine. Thermally harmful radiation has been the subject of the majority of studies. In order to produce infrared (IR) or ultraviolet (UV) radiation, lamps have been used. While IR is mostly absorbed by the water inside the plant, UV is absorbed in the epidermis (Marx *et al.,* 2012). Infrared radiators and lamps that run on propane exhibit properties resembling those of flaming objects.

Laser weeding

Lasers have been regarded as a reliable cutting tool for physical weed control. Only the weeds' meristems (growth centres), which have an impact on the entire plant, need be treated with lasers. When a plant is exposed to laser light, energy is absorbed by the tissue and typically converted to heat, which destroys the meristem. Focusing the laser light on the weeds at the proper place is crucial when using laser technology on a wide scale. The wavelengths of the laser being used determine how much laser light is absorbed by plant tissue. For weed management, only lasers with a high level of absorption in plant tissue should be employed. Weed species, wavelength, exposure time, spot size, and laser intensity all had an impact on how effectively weeds were controlled. The use of laser weeding robots can increase labour productivity, address the labour shortage, enhance the environment in which agriculture is produced, improve the quality of the work produced, reduce energy waste, better utilize available resources, and assist farmers in changing their traditional working conditions and methods (Ge *et al.,* 2013).

iv) Robotics

Information technology is used to make decisions about site-specific weed treatment in precision weed management. Now that agricultural robotics research has advanced, weed management using robots is a possibility. Four fundamental technologies make up an all-purpose autonomous robotic weed management system: guiding, weed recognition and identification, precision in-row weed control, and mapping. Four different intra-row robotic weeders for precision weed-management systems are currently on the market, according to Peruzzi *et al.* (2017): the Robovator (Frank Poulsen Engineering Aps., Hvals, Denmark); the Robocrop (Tillett and Hague Technology Ltd., Greenfield, Bedfordshire, England); the IC-cultivator (Machinefabriek Steketee BV, Haringvliet, The Netherlands); and the (Costruzioni Meccaniche Ferrari, Guidizzolo MN, Italy).

Robovator

The Robovator is widely employed in organic farming and is thought to be the most effective intra-row weed management technology. Based on the detection of the crop row and the size difference between the crop and weed, the Robovator system is intended to distinguish between the crop plant and weed. With the Robovator, each row has a camera, and images from the cameras are processed to determine the position of the crop. The computer then sends an instruction to the actuator to operate at the right point. A variety of crops were used to evaluate the Robovator intelligent cultivator. When compared to a regular cultivator, the Robovator decreased hand weeding time for lettuce and broccoli by 27% and 39%, respectively.

Robocrop

It is a steerage hoe-based cultivator installed on a tractor that has two hydraulically operated disc modules for each crop row and common inter-row cultivation blades. The crop plant is located as the cultivator moves along the row, and a revolving disc turns to align the cut-away portion of the disc with the crop plant being rescued. The discs are fixed to a depth control wheel and programmed to cultivate in the crop rows at a shallow depth (usually 20 mm). Crop damage is prevented because crop plant spacing varies by removing a piece from the disc's plan profile and rotating it in time with a forward motion to make sure the segment is constantly in line with the crop plant. The required inter-row space is 25 cm (Tillet *et al.,* 2008).

IC cultivator

For guidance, the IC-Cultivator uses cameras, one for each row, to track the location of the crop plants in real-time. The position of the plant is determined by its colour, size, and anticipated location. The device can quickly eliminate weeds from three to four crop plants along a row of 1.5 to 6 m working widths thanks to its modular design. Additional data can be gathered during the procedure, such as the crop's density, cover, and potential change in colour (Siemens, 2014).

Removeed

Real-time crop plant detection is accomplished using infrared light sensors by the Remoweed. Using cutting blades that can cut weed without endangering the crop, the machine removes weeds from both the inter- and intra-row space. It requires a minimum row distance of 27 cm and can remove weed from 12,000 crop plants per row per hour.

v) Eletrocution

Electric current is one of the non-chemical weed management techniques. The idea of using electrical energy to kill weeds was developed in the late 1800s, and several patents have been registered in the USA since 1890. The most modern electrical weed control technology uses a device powered by a tractor to eliminate persistent weeds in row crops after conventional chemical treatment (Vincent *et al.,* 2001). These microwave- or electric-current-based technologies are still neither practical nor affordable. The viability of these non-chemical weed control techniques requires further study.

vi) Drone application

Drones are ideal to identify weed patches. The main advantages of Drones compared to Unmanned Terrestrial Vehicles (UTVs) are the shorter monitoring/ surveying time they require and optimal control in the presence of obstacles, which is critical when working between crop rows. In a few minutes, Drones can cover many hectares flying over the field, thus providing the photographic material for weed patches identification. These images are processed via deep neural network, convolutional neural network, and object-based image analysis (Maes and Steppe, 2019). For weed identification by Drones, mainly three types of cameras are used for weed patches identification: RGB, multispectral and hyperspectral cameras. These cameras are very similar in terms of information obtained for the purpose of weeds identification. Indeed, the three camera types can recognize weed patches with good accuracy depending on flying altitude, camera resolution and UAV used. Drones have been mainly tested on important crops such as *Triticum* spp., *Hordeum vulgare*, *Beta vulgaris*, *Zea mays* (Louargant *et al.,* 2018). These are among the most cultivated crops worldwide and are highly susceptible to weed competition especially in early phenological stages. In these crops, it was possible to identify several dicotyledonous weeds including *Amaranthus palmeri*, *Chenopodium album* and *Cirsium arvense* (Huang *et al.,* 2018), as well as different monocotyledonous such as *Phalaris* spp., *Avena* spp. and *Lolium* spp. (Sanders *et al.,* 2019). Therefore, the combined use of Drones and image processing technologies may contribute to effectively control different weed species interfering with the crops.

vii) Automatic Spot Spray System

WeedSeeker® which is automatic spot spray system senses a weed when the weed enters the sensor's field of view, and this system signals a spray nozzle to deliver a precise amount of herbicide, spraying only on weeds and not bare ground. This machine uses advanced optics and computer circuitry to sense the presence of weed. Sensors and nozzles spaced at 30 or 38 cm apart compared to a 50 cm spacing on a standard boom. This system is most effective in areas where weeds occur intermittently. The narrower field of view associated with the WeedSeeker® sensors allows maximizing savings of herbicide. It reduces herbicide use by 60-90%.

viii) Harvest weed seed destruction

The development of new weed management techniques has been necessitated by the widespread multiple herbicide resistance in two of Australia's most significant weeds, annual ryegrass and wild radish (Walsh *et al.,* 2001, 2007). Australia has developed harvest weed seed management (HWSC) devices to target and eliminate weed seeds during the harvest of commercial grain crops, reducing weed seed inputs into the seed bank (Walsh and Powles, 2007). The biological characteristic of seed retention at maturity exists in annual ryegrass, wild radish, and several other annual crop weed species. This characteristic allows the weed seeds to be harvested (picked) during the harvest of grain crops because the seeds are still adhering to the erect plant. In order to target and eliminate weed seeds during the commercial grain crop harvest and reduce weed seed inputs into the seedbank, harvest weed seed control (HWSC) technologies have been developed in Australia.

Harrington Seed Destructor (HSD)

It is a trailer-mounted cage mill with transfer systems for chaff and straw and a diesel motor for power source. The HSD will eliminate at least 95% of the annual ryegrass, wild radish, wild oat, and brome grass seed present in the chaff fraction of harvest residues, according to an evaluation of the HSD during commercial wheat crop harvest. These findings support the HSD's potential as a technique for eliminating weed seeds during the harvest of grain crops.

Conclusion

Over the past few decades, there have been many innovations in weed management, but few of them can be used in conservation agriculture. The crop, the size of the weeds, and the kind of soil determine the sort of machine that can be used, and it should limit yield losses. Different types of weeders (Finger weeders, ECO weeders, Torsion weeders, etc.), microwave and laser technology, thermal treatment (flaming, burning, steaming, etc.), robotics, drone technology, and other satellite-based precision weed management technologies have emerged as suitable options for automation in weed management in CA, but only a few are affordable to the country's small and marginal farmers. To improve resource usage efficiency in mechanical weed management in India, more research is required to build a low-tech, low-cost device that would be easily accessible to farmers as well as to develop and implement precise weed management technology.

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National Symposium on Digital Farming: The Future of Indian Agriculture
2-3 February 2023, ICAR-IISS, Bhopal

Digital Agriculture: Prospects and Challenges in India

E.V.S. Prakasa Rao* and K.V. Ramesh

CSIR-Fourth Paradigm Institute, Bengaluru, Karnataka, India

**Email: evsprakasarao@gmail.com*

ABSTRACT

Emerging big data analytics and the digitalization of processes in all sectors are changing the course of progress globally. Among all the fields in the world, agriculture lags behind all the others in digitization; India is no exception. Industry 4.0 and the evolving agriculture 4.0 use the tools of big data analytics, IoT, sensors, satellites, drones, AI, cloud storage and computing, dynamical modelling, block-chains, and robots. India aims at an economy of $30 trillion by 2050 and agriculture plays a sustaining role; digital agriculture fast tracks economically and ecologically progressive agriculture in India. Digital agriculture involves the collection of data, modelling, data analytics, and AI, connectivity and control and also delivery of technologies. The use of deep space technologies, drones and sensors in the collection of data, dynamical modelling platforms, data analytics including statistical, machine learning and deep learning methods, and engineering design of farm machinery and agri-bots will be the future of agriculture in India. Customization of digital technologies to the majority of small farm holders, active participation of the private sector in developing revenue models and enabling policies of and implementation by the government of digital agriculture will fuel digital agriculture in India. Issues of data equity and data privacy will be key challenges for digital agriculture. Scientists across disciplines need to work in collaboration to develop technologies suitable to digital agriculture. We discuss the science processes required for digital agriculture and the roles of other players in the digital space of agriculture.

Key words: Data analytics, delivery, digital agriculture, modelling, sensors

Agriculture plays a vital role in India's economy. About 54.6% of the total workforce is engaged in agricultural and allied sector activities (Census, 2011) and accounts for 17.8% of the country's Gross Value Added (GVA) for the year 2019-20 (*https://agricoop.nic.in*). Climate change, depletion, and deterioration of natural resources, continuing genetic limitations, declining factor productivity, rapid changes in the socio-economic scenario, and rural migration are among the major road-blocks in agriculture. As Industry 4.0 has emerged in the industrial revolution worldwide, Agriculture 4.0 is touted as one important development in a new paradigm of agriculture; India is not an exception. Emerging tools of deep space technologies, drones, and sensors in the collection of data, dynamical modelling platforms, data analytics including statistical, machine learning and deep learning methods, engineering design of farm machinery and agri-bots are some of the ways to fuel Agriculture 4.0.

Digital technologies using big data analytics, IoT, sensors, satellites, drones, AI, cloud storage and computing, dynamical modelling, block-chains, and robots are going to stay and create a paradigm shift in agriculture (King, 2017; Himesh *et al.*, 2018). Big data and data analytics have been shown to improve agricultural processes (Ramesh *et al.*, 2020) which will greatly help decision-making processes in agriculture (Prakasa Rao *et al.*, 2021). Digital disruption has become more a necessity than a choice in the current complex agriculture (Prakasa Rao, 2022a,b). In the developed world, precision agriculture where plant and animal systems are managed to increase the efficiency and output of agriculture has evolved further with digital technologies (Cook, 2021). Prospects and challenges involved in Indian agriculture are discussed here.

Digital agriculture involves the collection of data, modelling, data analytics and AI, connectivity and control and also delivery of technologies. Social and ethical issues of the digitalization of agriculture need attention.

Collection of Data: Digital tools have enhanced the speed and accuracy of data collection in agriculture. NAAS (2021) has categorized data collection as:

- Scientific/Experimental/Survey Data/ Lab/Field
- Geo-referenced data
- Sequence/Genome data: Bigdata
- Live stream of images/data
- Socio-economic data
- Open Government Data Platform

The different tools of data collection include field sensors, remote collection-satellites, unmanned aerial vehicles (drones), and robots. Various types of sensors which could be fitted to farm equipment such as tractors, handheld, and field installed are used for data collection and are powered by IT and cloud computing to generate real-time on–field data. Recent advances in biosensing technologies and material sciences have played a crucial role in understanding agricultural process dynamics through molecular recognizing materials, antigen-antibody interaction and subsequent transduction mechanism (Sumana *et al.,* 2019). Recently, tiny, needle-like sensors inserted into plants are the latest addition to precision agriculture. Using micro-needles, a technology borrowed from medicine, researchers mine real-time data to make farming hyper-efficient and more sustainable (Bryce, 2021).

The popular satellite-based remotely sensed data used in agriculture are Moderate Resolution Imaging Spectroradiometer (MODIS), Landsat and Sentinel missions. The most important derived parameters from MODIS for crop-related studies are Land surface temperature, Land use Land cover, Vegetation Indices (NDVI and EVI), Fraction of Photosynthetically Active Radiation (FPAR), Leaf Area Index (LAI), Evapotranspiration, and Gross Primary Productivity. In the context of increased applications using free and open data at the regional scale, field-level data are essential for validation, successful analysis and interpretation.

Unmanned aerial vehicle (UAV)-based high-resolution multispectral imaging provides information to estimate crop and environmental states that can be used to monitor progress over time in site-specific farming to tailor specific crop and soil management for each field (Rudd *et al.*, 2017). Integration of unmanned aerial vehicle with satellite-based remote sensing images for decision-making has been suggested (Ramesh *et al.*, 2020) (Figure 1). In addition, the collection of regular field measurements facilitate an integrated data structure that enables modelling and data analytics.

Integrated modeling and data analytics: Meta-analysis helps primary research studies by placing them as substantial contributions within the larger picture of a research topic (Li *et al.*, 2020). Image processing and analytics and the challenges involved in image processing have been discussed (Ramesh *et al.*, 2020). Thermal imaging of wheat crop canopy and image analytics were used to

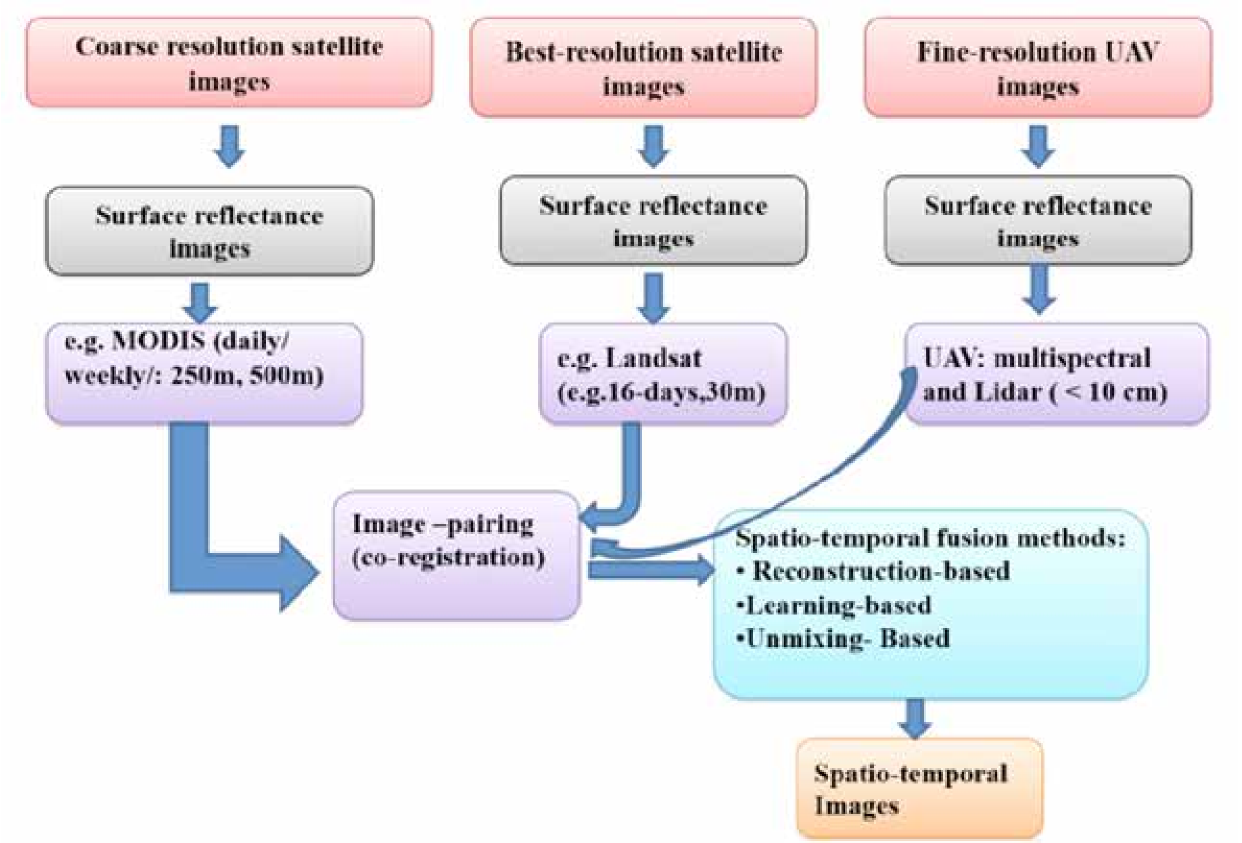

Figure 1. Framework for spatio-temporal multispectral image through fusion from multisource multispectral Images (Ramesh *et al.*, 2020)

estimate the leaf area index under different moisture stress conditions (Banerjee *et al.*, 2018). The Consortium for Research on Agroecosystem Monitoring and Modeling from Space (CREAMS), an initiative of the Indian Agricultural Research Institute, New Delhi, has been building capacity in using remote sensing, agro-meteorology and crop system models for qualitative and quantitative assessment of agricultural systems at the field and regional scale in India (*http://creams.iari.res.in/cms2/index.php*).

Crop models such as the Decision Support System for Agrotechnology Transfer-Cropping System Model (DSSAT-CSM) (Jones *et al.*, 2003) and Agricultural Production Systems sIMulator (APSIM) (Keating *et al.*, 2003), are extensively used in the analysis, evaluation, and prediction of crop growth and production at in-field scale up to regional levels using field-level weather, soil and field experimental data. Experimental studies have shown that incorporating phenology dynamics in such models can help to improve the accuracy of yield estimation (Fang *et al.*, 2011; Bolton and Friedl, 2013; Zhu *et al.*, 2018). Crop models require the extensive engagement of stakeholders which needs big data and large-scale and high-resolution crop phenology information. Integration of experimental field data with remote sense information and other environmental factors for yield estimation requires deep learning techniques such as Long Short Term Memory (LSTM) models which implement a Recurrent Neural Network (RNN) structure, representing a deep network structure for incorporating the crop-growth processes. The LSTM model has been proved to accommodate different types and representations of data, recognize sequential patterns over long-time spans and capture complex nonlinear relationships (Thornton *et al.*, 2014). Multi-dimensional and heterogeneous geospatial data for yield estimation requires an advanced and robust modelling approach; a schematic of the approach to integrate multiple components of a natural cropping system in an interactive predictive analytic platform is shown in Figure 2. Such an approach using region/ field-specific crop phenology information and deep learning-based time series structure can reveal cumulative and nonlinear effects, through the integration of systems associated in the cropping system with field observation, remote sensing, modelling and machine learning. The systems dynamical model (SDM) concept has been suggested which integrates various systems to enhance understanding of complex agro-ecosystems (Ramesh and Rakesh, 2019). Recently, mobile fluorescence sensing robot-aided by a machine learning (ML) model has been used with reasonable accuracies for determining canopy N variability at early growth stages of maize, which would help farmers in the optimal management of nitrogen (Siqueira *et al.,* 2022). Digital twins can transform agricultural production systems and supply chains, curbing greenhouse gas emissions, food waste and malnutrition; the potential of these advanced virtualization technologies is yet to be realized (Tzachor *et al.*, 2022). The AI-based systems are already helping farmers with soil analysis, planting, animal husbandry, water conservation and more.

Connectivity: Advances in Internet of Things (IoT)-based sensing systems have improved capabilities to precisely monitor crop parameters, thermal imaging and environmental conditions. These sensing systems are connected to a wireless sensor network (WSN) refers to a group of spatially dispersed and dedicated sensors for monitoring and recording the physical conditions of the environment and organizing the collected data at a central location. The modern networks are

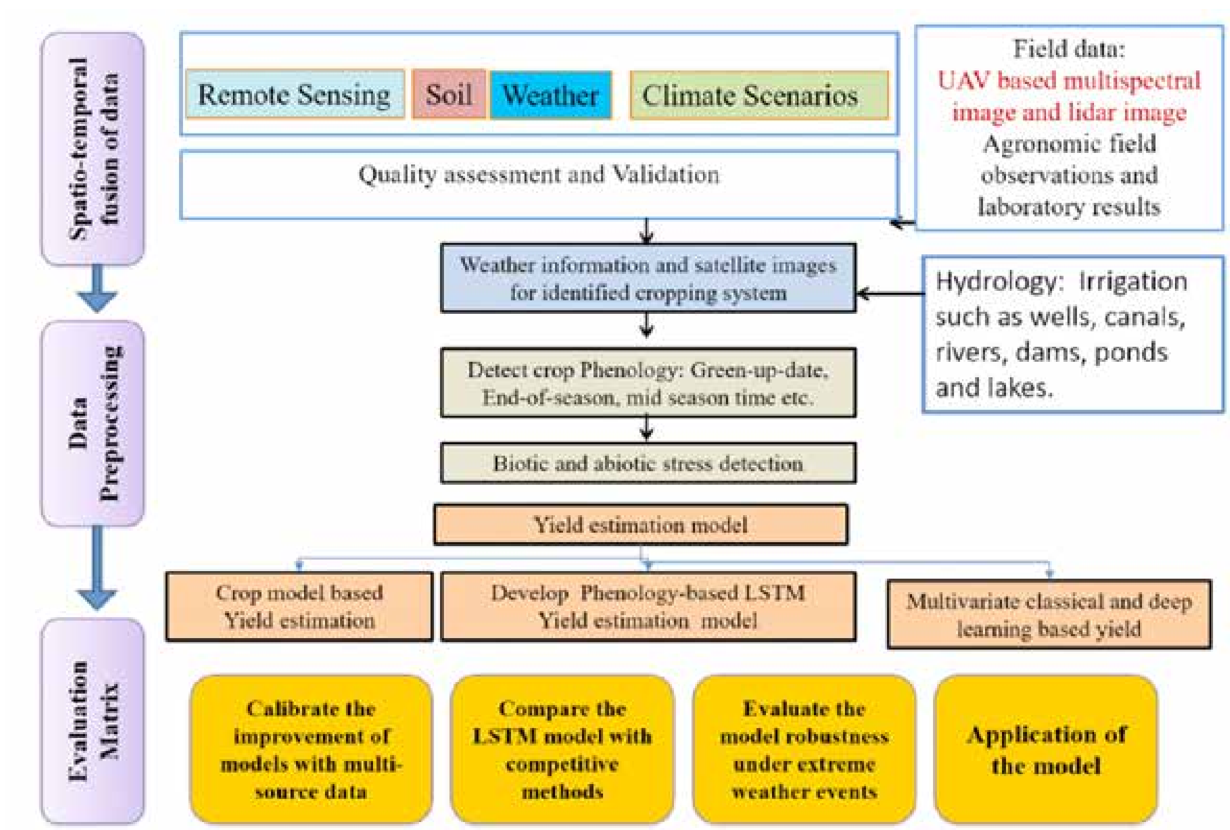

Figure 2. The basic structure of predictive analytics system for crop yield prediction (Ramesh *et al.*, 2020)

bi-directional, both collecting data from distributed sensors and enabling control of sensor activity. The IoT connected with WSNs will provide a basic framework for high-density data collection, for example, microclimate (temperature, relative humidity, rainfall, wind speed, solar radiation, etc.), soil temperature and moisture, etc. High-resolution sensing of agro-meteorological parameters help to solve critical issues about the crop-weather-soil continuum; for example, early identification or prediction of biotic and abiotic stresses in the crops. High-density and fast internet connectivity including in remote areas will fuel data connectivity and analysis in India.

Delivery and control: Modern data-driven smart farming has components of data acquisition, data transmission and application. The application component is mainly responsible for data analysis, early warning, automatic control and scientific decision-making. The frequency and surface resolution of remotely sensed multispectral images have grown and been established as useful tools in crop management. The applications of digital technologies include crop identification, crop acreage estimation, identification of planting and harvesting dates, identification of pests and disease infestation, crop-condition assessment and stress detection, soil-moisture estimation, irrigation monitoring and management, land cover and land-degradation mapping, etc. This helps in forecasting yields, monitoring plant stresses, and optimizing field practices to ensure the growing of healthy crops for better returns and resource use efficiency. The free accessibility to most of these data is another advantage for effective and timely utilization. Big data-driven farmer advisories could propel a new age of transparent and efficient agricultural value chains. Among the delivery advantages of digital technologies in agriculture are: efficient farm practices, minimization of soil, water, and air pollution, market intelligence and access, price negotiations for higher profits, and access to financial institutions for credit. A conceptual diagram is given (Figure 3) on the method of transferring the knowledge to farmers obtained by modeling and data analytics.

Roles of Public and Private Sectors

Government as enabler of digital ecosystem in the country has been at the forefront of promoting digital agriculture. Ministry of Agriculture and Farmers Welfare, GOI has launched 'India Digital Ecosystem of Agriculture' (IDEA) which serves as a platform called Agristack for services like direct

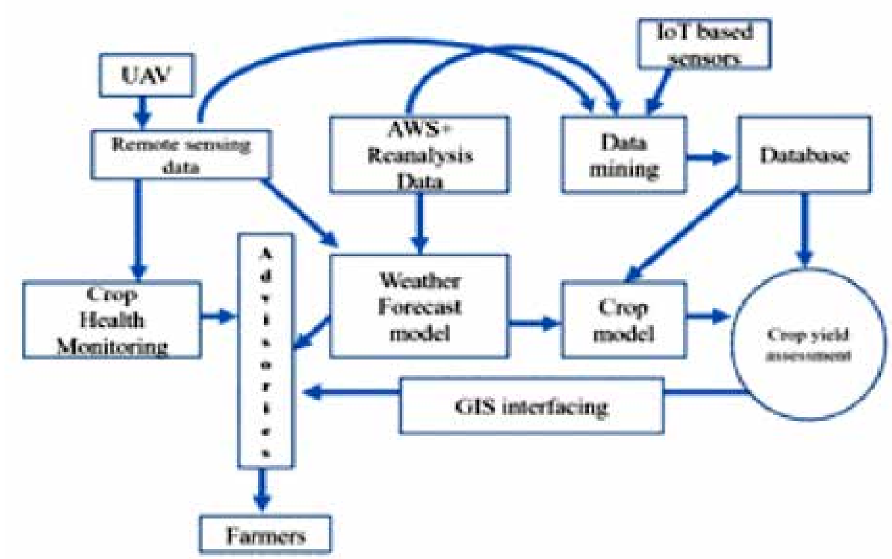

Figure 3. Big–data analytics platform for generating farm advisories (Prakasa Rao *et al.*, 2021)

benefit transfer, irrigation facilities, seamless credit, and insurance facilities, weather, soil, and plant health advisories (*https:// agr icoop.nic.inconsultati on paper*, 2021). The Kisan Drones programme unveiled by GOI in 2022 is expected to drive digital transformation of Indian agriculture along with economizing labor-intensive farm operations such as spraying, monitoring, and delivery. GOI set up eNAM (National Agriculture Market) an electronic trading portal to connect APMCs. Such apps as Pusa Krishi (agronomy advisories at the farm level) have been launched. Digital technologies to aid agriculture will be at the forefront of the government policy to create an ecosystem of developed agriculture in India.

The 370 billion dollar agriculture sector in India is transforming as technology and regulatory changes are emerging. And these changes are expected to result in 30-35 billion of value in agri-logistics, offtake and agri-input delivery by 2025. Investments in agritech increased from 91 million dollars in 2017 to 329 million dollars in 2020 (Anonymous, 2021) and are projected to reach 24 billion dollars by 2025. Big data analytics, supply chain/ market-linked models, FaaS (farming as a service) and IoT and engineering innovations are expected to occupy AgTech space in the future in India (PwC, 2018). AgTech is adopting digital technologies to make agricultural value chains more efficient, delivery of products which include input supplies, credit, real-time agronomy services, post-harvest handling and processing, transportation, storage, marketing, traceability, and insurance and create rural employment generation and farm prosperity (FICCI-PwC, 2022).

Equity and Ethics of Digital Agriculture

Although digital agriculture provides wide opportunities in terms of improved productivity and low environmental foot-print, only recently socio-ethical challenges involved are being debated. Responsible research and innovation (RRI) have been suggested (Eastwood *et al.*, 2019). More structured and controlled farming by digital technologies poses the dangers of impacting the social fabric and dominance of input suppliers, digital companies, manufactures of agricultural machineries and equipments such as sensors, network systems, processors and traders. Prakasa Rao *et al.* (2021) have raised the issues of data privacy in India where the data of millions of farmers are captured, and often times are processed outside the country. They have suggested that mechanisms should be put in place to protect data privacy, evolve methods of compensation for data sharing and establishment of a data regulatory authority to protect the interest of farmers.

Conclusions

Digital agriculture will usher in Agriculture4.0 where a new paradigm shift in improved systems of higher productivity, resources use efficiencies, farmers' income, low environmental foot-print, rural entrepreneurship, and national economy emerge. However, evolving socio-equity-ethical issues need continued attention to bring digital agriculture to a logical advantage.

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National Symposium on Digital Farming: The Future of Indian Agriculture
2-3 February 2023, ICAR-IISS, Bhopal

Linking Space Technology to Crop Modelling for Better Decision-making in Agriculture

R.S. Chaudhary*, Nishant K. Sinha, Dhiraj Kumar and J. Somasundaram

ICAR-Indian Institute of Soil Science, Bhopal-462 038, Madhya Pradesh

**Email: rschaudhary6691@gmail.com*

ABSTRACT

A broad scope of crop models linked with inputs from satellite data has been recognized for multiple important purposes, such as possible adaptation strategies to control the impact of climate change on future crop production, management decisions, adaptation policies, crop forecasting, etc. Crop modeling can play an important role in food security, safety, and decision-making. But, the major limitations of crop growth models are the missing spatial information for a larger application. The inputs from space technology can integrate with crop models to provide the missing data for decision-making at the regional scale. In fact, an accurate and in-time crop forecast will help decision-makers to implement corrective measures well in advance to reduce the risks of climatic variability. Agriculture being highly dynamic, depends on variable resources and climatic conditions. Therefore, real-time monitoring of resources and crops needs to be done by employing the latest space technologies, such as RS and GIS coupled with crop models. It adds for pinpointing any changes to be made in-season for crop production, and estimates in advance could guide us for adaptation to avoid any crop damage/failures. In recent times, due to climate change and complex weather abnormalities, there is great scope to link crop models with space technology to provide recommendations for policymaking at the government level to support resource-poor farmers.

Key words: Agri-food systems, Crop modeling, Crop management, Satellite data, space technology

Introduction

Agriculture is one of the major economic sectors providing food to billions, but the current yield growth and overall production are insufficient to satisfy the future food demand (Grassini *et al.*, 2013). Further, climate change is predicted to add another 60 million people hungry by 2050 (Wiebe *et al.,* 2015). The water supply will fall 40% short of meeting global needs by 2030 (World Resources Report, 2013), and the rising cost of labor, nutrients, and energy further pressure profit margins. Furthermore, around one-quarter of the arable land is degraded and thus needs significant restoration. In the absence of coordinated efforts to raise productivity, consumers may have to pay double the price of staple foods by 2050 in real terms (Rosegrant *et al.*, 2013). Thus, concerted efforts using the latest knowledge are needed to improve decision-making for making agriculture profitable and reduce the risk of food insecurity in the face of climate change and a resource-poor environment. Therefore, it is inevitable to embrace digital transformation in agriculture.

Monitoring crop growth and yield forecasting are of immense importance for planners and policy-makers at the national level to food security. Reliable, timely, and credible information also enables planners and decision-makers to optimally handle deficits/surpluses of food crops in a given year. Here comes the role of crop modeling in providing accurate information for appropriate decision-making. Modeling can provide a better understanding of crop performance and yield gaps, better prediction of pest and insect outbreaks, and improve the efficiency of crop management, including irrigation systems and optimization of planting dates. Recently, remote sensing data, GIS techniques, mobile technology, and crop simulation models have provided a greater opportunity to develop the decision support system for crop management.

Crop models often require comprehensive weather data for simulations, which is often not available or insufficient. Other data on soil types, fertility, and physical environment are also lacking at different spatial scales. Therefore crop modeling approaches are still limited by the availability of quality data. However, there is a great scope for using space technology to fill the data gaps. A model can be integrated with real-time, frequently updated, high-resolution satellite data for real-time monitoring at regional scales. Further, remote sensing with a variety of sensors already allows monitoring and acquisition of surface soil moisture and solar radiation, as well as soil chemical and physical properties.

Spectral analysis of high-resolution satellite images enables the performance of real-time monitoring of crops as well as tracks the dynamics of crop development. In addition to crop health and change detection, space-borne platforms provide inputs for environmental analysis, irrigated landscape mapping, yield determination, and soil analysis. When integrated in decision-making models, all of these techniques may inform of the necessity of specific agricultural interventions in particular field zones (Fig. 1).

In their simplest form, crop models represent a quantitative axiom (e.g., growth = light interception x radiation use efficiency) backed by a large body of empirical data. Where data is lacking, a model may constitute a qualitative but testable hypothesis (i.e., a conceptual model, whether biophysical or socio-economic). More complex quantitative or semi-quantitative simulation

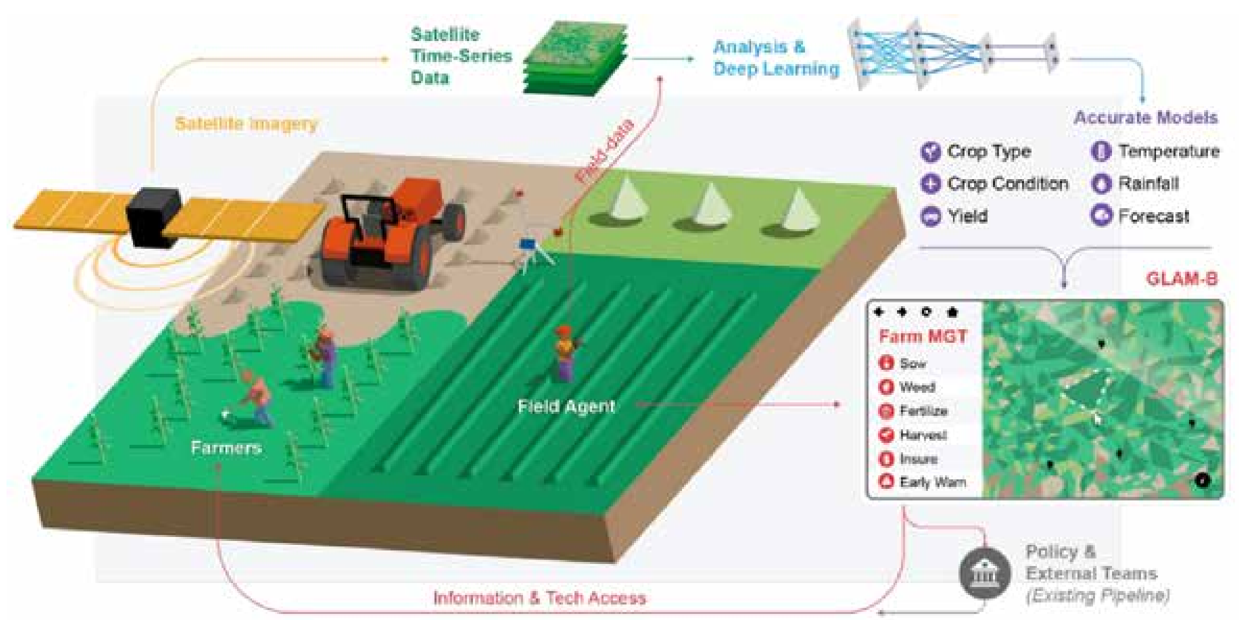

Figure 1: Space technology and crop monitoring (Source: (https://unfccc.int/)

models can be developed by combining such elements. Crop productivity models within the framework of the widely used conceptual model G x E x M (GEM), represent the three most important biophysical variables that directly determine crop growth, and their interactions. Namely, expression of the genetic potential of a cultivar (G), the physical environment of the crop (E), and crop management inputs (M).

Commonly used Crop Models

The use of crop models and their application in the agricultural field started in the 1970s. Still, different types of models are increasingly accessible for practitioners with varying levels of exposure and expertise. A comprehensive list of the available models are listed in Table 1.

Table 1. Most commonly used crop models

Crop Models	References
DSSAT	Jones *et al.* (2003)
APSIM	McCown *et al.* (1996)
SALUS	Basso *et al.* (2012)
Aquacrop	Steduto *et al.* (2009)
ORYZAv3	Li *et al.* (2017); Bouman, and van Laar (2006)
SWAP	Huang *et al.* (2015)
FarmSim	Di Paola *et al.* (2016)
DAISY	Palosuo *et al.* (2011)
CROPGRO-Soybean	Bachelor *et al.* (2002)
HERMES	Palosuo *et al.* (2011)
STICS	Brisson *et al.* (1998)
SUCROS	Bouman (1992)
Fasset	Olesen *et al.* (2004)
Cropsyst	Stöckle *et al.* (2003)
CERES-wheat	Lobell and Burke (2010)
EPIC	Di Paola *et al.* (2016)
ROTASK	Clevers *et al.* (2002)
WOFOST	Van Diepen *et al.* (1989)
AgromeShell	Di Paola *et al.* (2016)
GLAM	Challinor *et al.* (2004)

To explain a few, let us begin with EPIC. Environmental Policy Integrated Climate (EPIC) model is a traditional decision support system based on crop simulation models and is site-specific. To address the effects of spatial variability of soil conditions and weather variables on crop production from one region to other, *GIS is linked with the biophysical agricultural management simulation model EPIC, which is known as Spatial-EPIC. This model can be applied to any size of agro-system, from field to country, and even bigger areas can be modeled. The spatial-EPIC system's file structure comprises text files, which contain an estimate of parameters of different physical processes modeled by Spatial-EPIC.* These files include basic user-supplied data such as crop, tillage, pesticide, and daily weather parameters. *ArcView 3.1 is used as a pre-and post-processor for data furnishing and a graphical display of Spatial- EPIC. Some sub-models of Spatial-EPIC are soil, weather, plant environment, and crop growth.*

APSIM is a modeling framework that allows individual modules of key components of the farming system (defined by model developer and selected by model user) to be 'plugged in'. The model was developed to simulate the biophysical process in farming systems, particularly where there is interest in the economic and ecological outcomes of management practice in the face of climatic risk. APSIM's structure provides details of the concepts behind the different plant, soil and management modules. These modules include a diverse range of crops, pastures, and trees, soil processes including water balance, N and P transformations, soil pH, erosion, and a full range of management controls. *That way the model provides plug in access to spatially derived data on crop canopy, soil water, soil properties and other environmental/weather data.* APSIM has been used in a broad range of applications, including support for on-farm decision-making, farming systems design for production or resource management objectives, assessment of the value of seasonal climate forecasting, analysis of supply chain issues in agribusiness activities, development of waste management guidelines, risk assessment for government policy-making and as a guide to research and education activity.

The SALUS (System Approach to Land Use Sustainability) model, is designed to simulate continuous crop, soil, water and nutrient conditions under different management strategies for multiple years, taking into account several aspects such as crop rotations, planting dates, plant populations, irrigation and fertilizer applications, and tillage regimes. Its extension, i-Salus is also a web-based agronomic decision support system. *i-Salus comprises two interfaces: a simple interface and a Web-GIS interface.* SALUS, with its simple interface, is a user-friendly system that targets farmers or extension specialists who can simulate the impact of different management strategies on yield and environmental impact. *SALUS-WebGIS is a web-based GIS integrated with Google Earth which simulates the effect of climate-soil-genotype-management interaction on crop yield and environmental impact in a spatially explicit manner.*

CropSyst is a multi-year, multi-crop, daily time step cropping systems simulation model developed to serve as an analytical tool to study the effect of climate, soils, and management on cropping systems productivity and the environment. CropSyst simulates the soil water budget, soil-plant nitrogen budget, crop phenology, canopy and root growth, biomass production, crop yield, residue production and decomposition, soil erosion by water, and salinity. The main components of the CropSyst Suite are: CropSyst parameter editor, a cropping systems simulator (CropSyst model), a weather generator (ClimGen), *a GIS-CropSyst simulation co-operator (ArcCS),* a watershed analysis tool (CropSyst Watershed), and several utility programs. The cropping systems simulator is the core of the suite of programs.

The above examples of crop models indicate that space technology has started integrating with the models for better data input and accurate outputs toward the right agricultural decision-making.

Input data for crop models

A minimum amount of input data is needed for operating crop growth models. Crop modeling requires information regarding crop, soil, weather, management, insect-pest and phasic development data. Input data may have several ranges ranging between hourly, daily, weekly or monthly time frames (Nix 1983). Therefore, almost each of the above data files has a great scope to be linked with satellite-derived data, which is updated and more precise to temporal and spatial scales. Linking the input data files of crop models with space-derived data may improve the precision of the information derived toward appropriate decisions in agriculture (Fig. 2).

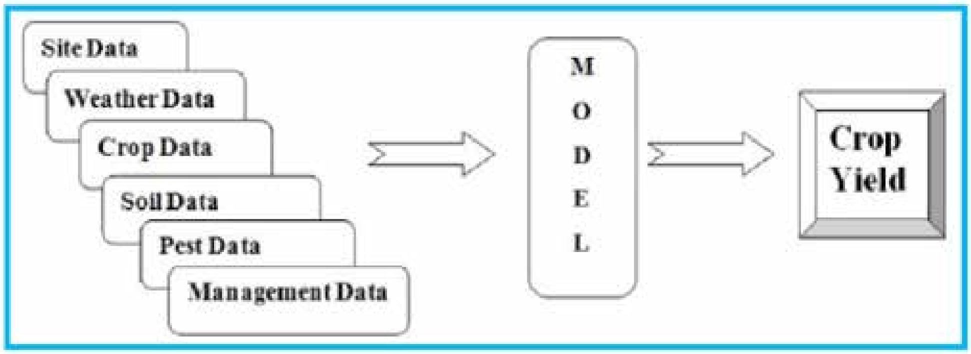

Figure 2. Inputs for crop growth models. Source: (Kaur and Singh 2020)

Table 2. Minimum input data set for crop growth models (Source: Hunt and Boote 1998)

1. **Site**
- Latitude and longitude, elevation
- Average annual temperature
- Slope and aspect

2. **Weather**
- Daily global radiation, maximum and minimum temperatures, precipitation

3. **Soils**
- Soil type
- Soil depth, root growth factor, bulk density
- Organic carbon, pH, soil nitrogen

4. **Initial conditions**
- Previous crop, root nodule amounts
- Water, ammonium and nitrates by soil layer

5. **Management**
- Cultivar name and type, planting date, depth and method, row spacing and direction, plant population, irrigation and water management (dates, methods and amounts)
- Fertilizer (inorganic) and inoculant applications
- Residue (organic fertilizer) applications (material, depth of incorporation, amount and nutrient concentrations)
- Chemical (e.g., pesticide) applications (material, amount)
- Tillage
- Harvest schedule

Applications of Crop Models in some important aspects of Agriculture

(a) Assessing Impact of Climate Change

Climate change poses a considerable threat to global food security. It directly impacts food production through crop yield changes, typically from temperature increases and rainfall variability. Climate change also adversely affects soil health by reducing soil organic matter content (Mohanty *et al.,* 2020), decreasing soil structure, and increasing vulnerability to erosion and other degradation processes (Brevik 2013). It also reduces the nutritional quality of agricultural produce. Recent research has shown that under highly elevated atmospheric carbon dioxide (CO_2) concentrations, iron and zinc content in plants could fall by as much as 17%, accompanied by increased starches and sugar production (Myers *et al.,* 2015).

Climate change and variability account for nearly 60% of yield variability, making it a critical factor in food production and farmer income (Ray *et al.,* 2015; Matiu *et al.,* 2017). The annual average maximum temperature in South Asia (SA) is expected to rise by 1.4-1.8°C in 2030 and 2.1-2.6°C in 2050, resulting in a 12% increase in heat-stressed areas in 2030 and a 21% increase in 2050 (Tesfaye *et al.,* 2017). According to projections, due to heat stress, nearly half of the Indo-Gangetic Plains (IGP) will become unsuitable for wheat production by 2050 (Ortiz *et al.,* 2008). A general rule of thumb in the equatorial tropics is that every 1°C rise in mean temperature is associated with a 10% drop in crop yields (Brown, 2008). In India, a study showed that increasing the temperature by 1°C with no change in rainfall resulted in a decline of 10-15% soybean grain yield. Delaying sowing dates (20 June to 10 July) and increasing the plant density to 60 plants/m^2 of soybean crop could be viable adaptative strategies against climate change (Mohanty *et al.,* 2016, 2017). For maize, increasing temperature by 1°C could reduce the grain and biomass yield by 10% and 8%, respectively. This decrease in maize yield attributed to a decrease in the crop duration as a one-degree increase in temperature may decrease the crop duration by 4.3 days. Adopting the sowing date between 7th and 14th July may reduce the impact of temperature change on maize grain and biomass yield in central Indian conditions (Patidar *et al.,* 2020). Even it was observed that the CO_2 fertilization effect was masked by the increase in temperature under different climate scenarios on maize grain and biomass yield (Sinha *et al.,* 2021).

Further, 1°C temperature increase without an increase in CO_2 concentration reduces wheat grain yield by 8.4% and biomass yield by 7.8%. While 4.5°C temperature increase without an increase in CO_2 concentration reduces wheat grain yield by 39% and biomass yield by 37%. Simulation approaches showed that when the water supply is ample, by applying 60 mm of water at 20 days interval in 5 splits to offset climate change. Under deficit irrigation, using the water in the increased number of splits would be a better option. Other studies conducted in India revealed that an increase in temperature (< 2 °C) led to a 5.2% decrease in wheat yield (Gupta *et al.,* 2017), 6%-8% decrease in rice yield (Saseendran *et al.,* 2000; Mathauda *et al.,* 2000; Mohanty *et al.*, 2015) and 10-30 % decrease in maize yield (Kalra *et al.,* 2007). In Bangladesh, a temperature increase of less than 3°C led to a decline of 2.6-13.5% in rice (Basak *et al.,* 2009) and a 60% decrease in wheat (Karim *et al.,* 1996). On the other hand, an increase in temperature up to 4°C could increase wheat yield by 8.6% in Nepal (Malla, 2008). Such scientific studies examined the significant impacts of climate change on major food crops in South Asia. Climate change shifts cropping systems, seasons, choice of crops and crop management practices. One clear example is the shifting of spring maize growing periods and delayed sowing of autumn maize during 1980-2014 in Pakistan (Abbas *et al.,* 2017). It had not only negatively affected the yield but also the livelihood of several farmers of Pakistan. Such concerns have been increasing due to the increasing climate change and its associated change in temperature and precipitation.

(b) Monitoring and Managing Pests and Diseases

Pests and diseases are an ever-present threat to crops worldwide, since they continually evolve to new pathotypes. As climate change and weather fluxes make it harder to predict their spread and virulence, multi-variable predictive models are becoming even more valuable as tools for crop protection. For pests, models can link organisms' physiological and phenological behaviour to environmental factors. For disease modelling, the life cycle is often represented by an infection chain, which corresponds to functional traits that can be converted to quantifiable processes and their responses linked to biological and environmental factors.

These tools are being used to answer several relevant questions, such as: (1) how can we predict pest/disease vector population and disease transmission dynamics in the presence of multiple factors? (2) What impact do control agents have within an integrated pest management system? (3) How can we better understand and predict pest/disease propagation patterns over time and space? and (4) What are the priority locations/regions for conducting risk assessments and limiting potential invasions of pests/diseases? Modelling for pest and disease management generally utilizes an inductive or deductive approach. In the inductive ("top-down") approach, pest/disease occurrence is linked to the prevailing bio-climatic variable in a specific area, and then used to predict the likelihood of that organism occurring in another area. Algorithms such as Maximum Entropy and Genetic Algorithms for Rule Set Production utilize the inductive approach. The deductive ("bottom-up") approach starts by modeling a species' response to climate variables and applies the model to predict the climate suitability of the organism.

One example of a deductive approach is applied in the Insect Life Cycle Modelling (ILCYM) open-source software package, developed by the International Potato Centre (CIP). ILCYM supports the analysis of life table data of insect species obtained from laboratory studies at constant temperatures and estimates, step-by-step, a mathematical expression to represent the species' development time, development rate, mortality, senescence, survival, and reproduction. Functions derived for each stage are combined to give a process-oriented, temperature-driven, and age-stage structured insect phenology/population model. Linkages between the phenology model and the landscape are based on geo-reference daily/monthly minimum and maximum temperature values using a cosine or sinus function to mimic patterns under natural conditions. Further, three risk indices (establishment, generation, and activity) are derived to assess the potential distribution and abundance of the pest in a given location.

(c) Crop Models for Management Practices

Crop simulation models have been successfully deployed in developed countries to manage farm resources, including crop choice, crop variety, sowing date, plant density, irrigation, and nitrogen and phosphorus inputs, but the quality of input data remains a challenge. These include management options such as using disease-resistant varieties, modified tillage, soil additives, micronutrients, changing row geometries, and more precise timing and placement of fertilizers, drip irrigation, use of surface mulches for modification of crop microenvironment and erosion. There is a case study on "Exploring Sustainable Crop Management Options to Reduce Groundwater Table Decline in North-west India". Irrigated rice in northwest India is entirely dependent upon groundwater pumped from the underlying aquifer, resulting in alarming rates of reductions of the groundwater table and the potential for saline groundwater intrusion into fresh groundwater. There is, therefore, great interest in finding sustainable solutions to arrest the decline in groundwater depth. The Agricultural Production Systems sIMulator (APSIM) crop model was applied to evaluate the effects of different crop management practices (rice variety duration, sowing date, replacing rice with other crops, and the use of conservation agriculture) on the land and water productivity of the total system, and on the components of water balance (Singh *et al.*, 2015). This approach can be extended to **rainfed rice systems** worldwide as a risk-reducing strategy in a variable monsoon. The simulations gave the following results:

- If minimizing permanent water loss from the system is the objective, the best method is a partial conservation agriculture rice-wheat system with a short-duration rice variety.

- If maximizing productivity is the sole objective, a full conservation agriculture system with a medium-duration variety is the best option.
- If the objective is to produce the maximum output per unit of evapotranspiration, this can be achieved using a short-duration variety planted in mid-July under full conservation agriculture.
- Replacing rice with rainy season maize (*Zea mays* L.) in the system can maintain yields while reducing the total irrigation amount by ~80%, which can contribute to huge reductions in pumping costs and energy use. Maize-based systems also reduce permanent water loss from the system by 200 mm.

There are several other examples/case studies, where Crop Simulation Models have proved successful in yield gap analysis, predicting effects of the interaction of environment with crop management on crop growth and yield, aiding in genetic improvement, irrigation scheduling, altering root-related genetic traits, modelling socio-economic factors and calculating food systems risks.

Linking space technology with crop growth models: How, when and where?

Remote sensing technology can provide useful information when combined with crop growth models. In the early 1970s, the idea was forwarded that data from satellites may increase the accuracy of crop models. There are three methods for combining remote sensing data with crop growth models. The first is an indirect approach, where RS data is assimilated with simulation model, either by calibration or feedback loop to adjust the model (Delecolle *et al.,* 1992). This method provides canopy measurements as a variable for the model and the spatial and temporal information of the data. Further, the other two methods involve integrating RS data with the crop model through forcing or recalibration (Mass, 1988). During the process of forcing, the model variables used to be replaced or adjusted using RS data, and during recalibration, the parameter or initial conditions got adjusted based on RS data. CLAIR model, a semi-empirical model was used for estimating LAI of wheat fields using SPOT as well as ground-based data in southern France (Clevers *et al.,* 2002). In this estimation, Weighted Difference Vegetation Index (WDVI) was derived as a difference between measured NIR and red reflectance, assuming the ratio of NIR and red reflectance of bare soil as constant. This estimate improved regional crop yield estimates and acts as a valuable tool for planners and policy-makers.

Another method of RS data incorporation with CGMs was proposed by (Mass, 1988). Crop model consists of three parts; state variables, driving variables, and parameters. The easy one being RS data should be used to evaluate one or more driving variables. Further, re-initialize or re-calibrate the model, also called the assimilation method, where RS data can be used directly to re-calibrate the model. It has been reported that data assimilation may fail to find the errors in modeled values, so a new strategy was adopted to reduce the difference between observation and simulation by adopting either vague model parameters, the initial conditions, or model state variables. The Ensemble Kalman filter (EnKF) is used frequently as an algorithm that assumes that the posterior density of every step is a Gaussian distribution parameterized by a mean and a covariance (Jiang *et al.,* 2014).

The standard EnKF method tends to reject observations in favor of the ensemble forecast in the late period of data assimilation, which could lead the analysis to deviate incrementally from the reality, which is referred to as filter divergence (Schlee *et al.,* 1967; Fitzgerald, 1971; Burgers *et al.,* 1998; Ines *et al.,* 2013). To reduce the effect of filter divergence, an inflation factor is often adopted to enlarge Kalman gain (Lin *et al.,* 2008; Huang *et al.,* 2016). The satellite-derived data provides direct and uncertainty-quantified component estimates of state vectors, i.e., LAI, that can be linked directly to model predictions. Kalman filters used to be a good choice if the data product's error statistics were Gaussian. As most of the CGMs are non-linear, thus the use of EnKF is practical way of assimilation (Table 3).

Table 3. Representative research on filtering approaches (Source: Huang *et al.* 2019)

Algorithm	CGM	Variables	EO data	References
CGKF	SWAP	LAI, ET	MODIS	Vazifedoust *et al.* (2009)
	MCWLA-Wheat	LAI	GLASS LAI (MODIS based)	Chen *et al.* (2018)
EnKF	WOFOST	LAI	MODIS	Wu *et al.* (2011); Zhao *et al.* (2018); Zhu *et al.* (2010)
	WOFOST	LAI	Landsat ETM+	Li *et al.* (2014)
	WOFOST	LAI	MODIS, Landsat TM	Huang *et al.* (2016)
	WOFOST	LAI	HJ-1A/B	Ma *et al.* (2013); Cheng *et al.* (2018)
	WOFOST	LAI	PROBA/CHRIS	Wang *et al.* (2013)
	WOFOST	LAI	SPOT, ERS, Radarsat	Curnel *et al.* (2011)
	WOFOST	SM	ERS, EUMETSAT	De Wit and van Diepen (2007)
	WOFOST	SM	SMOS	Chakrabarti *et al.* (2014)
	WOFOST	LAI, SM	Synthetic data	Pauwels *et al.* (2007)
	WOFOST	LAI, SM	AMSR-E, MODIS	Ines *et al.* (2013)
	DSSAT	LAI, SM	MODIS, SMOS	Nearing *et al.* (2012)
	DSSAT	LAI, VTCI	Landsat TM, ETM+ and OLI	Xie *et al.* (2017)
	SAFY	LAI	HJ-1A/B, Lansat-8	Silvestro *et al.* (2017)
EnSRF	WheatGrow	LAI, LNA	HJ-1A/B, Landsat-TM	Huang *et al.* (2013)
	DSSAT	LAI, SM	MODIS, AMSR-E	Mishra *et al.* (2015)
	SWAP	SM	SMOS	Singh and Panda (2015)

Note: CGKF, EnKF, EnSRF, VTCI represent constant gain Kalman filter, ensemble Kalman filter, ensemble Square Root Filter, Vegetation Temperature Condition Index.

Recently, Gumma *et al.* (2021) published an approach for the assessment of village-level crop yield using remote sensing, field data, and crop simulation models. Remote sensing products such as Sentinel-2 and Landsat 8 time series data were used and calibrated with field observed data. They derived a spatial variation map of crop extent, crop growth stages and leaf area index (LAI), for yield assessment. Crop classification was performed on Sentinel-2 time series data using spectral matching techniques (SMTs) and crop management information collected from field surveys along with ground data. The LAI was derived from SAVI (soil-adjusted vegetation index) equation using Landsat 8-time series data. Further the re-parametrization of crop simulation models was done through several iterations using remote sensing derived leaf area index (LAI). The data assimilation approach helps fine-tune the initial parameters of the crop growth model and improves simulation with the help of remotely sensed observations. Results showed a good correlation between observed and simulated crop yields ($R^2 \geq 0.7$) for all the crops (Rice, maize, Groundnut) studied. The schematic diagram of data assimilation approaches for combining remote sensing data with crop growth models to estimate crop yield is presented in Figure 3.

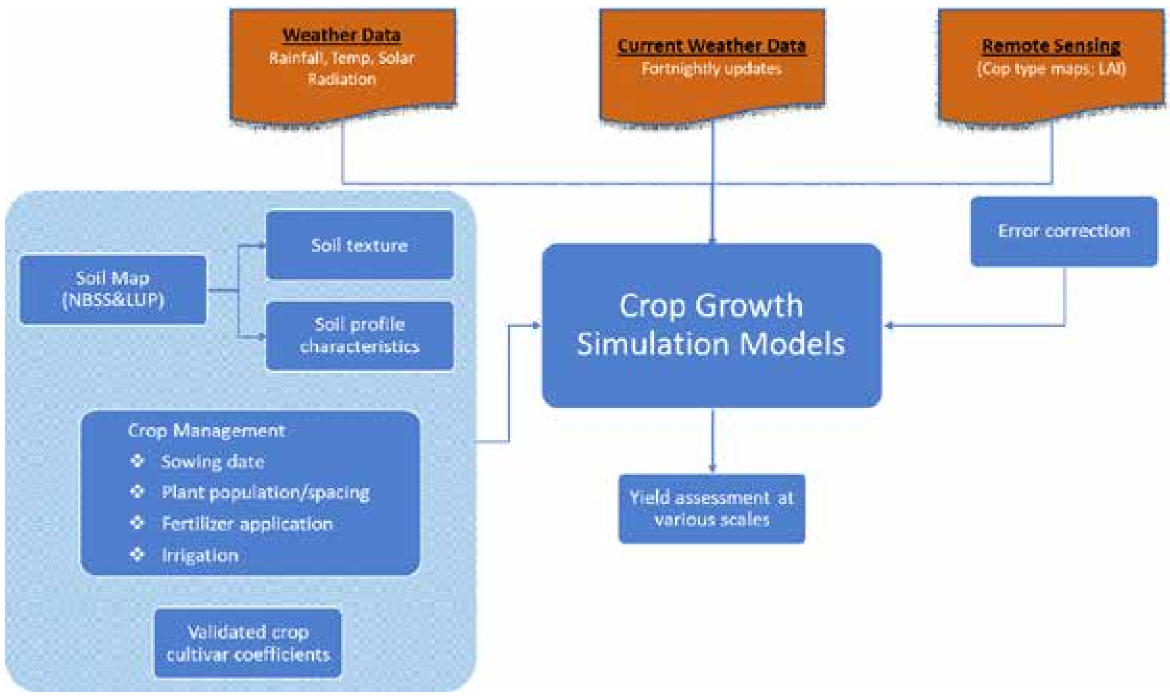

Figure 3. The data assimilation approach combines remote sensing data with crop growth models to estimate crop yield (Adapted from Gumma *et al.*, 2021)

Limitations

Satellite data-based modeling made extraordinary advancements with respect to data acquisition, processing, analysis, and utilization. Nowadays, several government agencies are directly using remote sensing and GIS data for crop forecasting, advanced estimates etc. However, the major limitations of modelling include unrealistic projections of climatic events, high variability in fields at small distances, misuse of models, lack of input data availability, complex processes in biological systems, errors during sampling leading to poor input data, rudimentary methods of validation, non-availability of optical remote sensing data during Kharif season due to clouds, spectrally similar crops or minor crops where assessment is difficult. Moreover, many satellite-derived parameters like evapotranspiration, soil moisture, rainfall etc. have a low spatial resolution, especially for the non-cereals crop, where the correlation between vegetation indices and crop yield is relatively low.

Way Forward

The use of satellite data for crop modeling has gone through many developments, viz., availability of data from very high-resolution remote sensing, even from moderately high-resolution satellites like Sentinel and Landsat, and launching of high-resolution satellites constellations like PlanetLab. Therefore, there is a need to develop high-quality, well-calibrated products for high-resolution biophysical and agro-meteorological parameters. These datasets with AI and physically driven models will lead to better forecasts and estimates of crop productivity and other information at the farm level. In this way, remote sensing technology coupled with crop models will play an important role in revolutionizing agriculture. These days, data availability from open sources such as Google Earth Engine, free RS and GIS tools like QGIS, SNAP, etc has further paved the way for better prediction.On the other hand, developments in Cloud Computing, the Internet of Things (IoTs), Artificial Intelligence (AI), Machine Learning (ML), Big Data Analytics, etc., along with better navigation satellites and communication system, has led to a paradigm shift in the RS data application. Indian Space Research Organisation (ISRO) had also planned many new satellites for dedicated use in agriculture, having a working range in the microwave and optical domains for providing medium-resolution data for geostationary platforms. Many start-ups are also working to offer RS data services for a number of end users.

Conclusion

A systematic agri-food system is pivotal to meet global challenges of food security. The shift in focus from an individualistic approach to a system approach has opened new vistas for crop modeling to predict the impact of changes on development. Integrating satellite data with crop modeling should benefit from future changes in remote sensing platforms by employing nanosatellites, planned space missions, UAVs, highly sensitive sensors etc. Of course, the accuracy level will be highly dependent upon the data quality, data acquisition, the complexity of handling big data, etc. Solutions to these problems significantly enhance the capability of models to assess the impact of climate change on an agricultural production system and forecast better agro-meteorological conditions. This way, the crop modeling coupled with reliable input datasets will revolutionize the management of resources and generate valuable information at the farm level, which may be useful to the farmers and the policy-makers at large.

Acknowledgment

The authors express their gratitude to the President, Indian Society of Agro-Physics for providing the opportunity to write the present review. The contents and opinions expressed herein are those of the authors and do not necessarily reflect the views of the associated and/or supporting institutions.

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National Symposium on Digital Farming: The Future of Indian Agriculture
2-3 February 2023, ICAR-IISS, Bhopal

Integrating Precision Agriculture Tools with Conservation Agriculture for Higher Nutrient Use Efficiency

A.K. Biswas, K.M. Hati, Pramod Jha, A.K. Vishwakarma and B.P. Meena

ICAR-Indian Institute of Soil Science, Nabibagh, Berasia Road, Bhopal-462038, Madhya Pradesh

ABSTRACT

Conservation of natural resources is the base for a long-term sustainability of agricultural and natural ecosystems. Conservation agriculture (CA) practices have clearly shown advantages in improving soil, water and air quality as well as reducing costs of operations and inputs over conventional agriculture. Variability must be considered both in space and time in order to achieve the ultimate goal of sustainable cropping systems because the factors which affects crop yield have different spatial and temporal variability. Advances in technologies such as Global Positioning Systems (GPS), Geographic Information Systems (GIS), remote sensing and simulation modeling provided a niche to assess the spatial and temporal variability present in the field and manage it with appropriate site-specific practices. Such approach is commonly called Precision Agriculture (PA) or site-specific crop and soil management. PA tools, which encompass precision mapping, soil sensors, and yield monitors, can be used to gather data on soil conditions, crop growth, and other factors that could be used to make site-specific nutrient management decisions. This can help farmers in optimizing CA practices, such as application of nutrient, crop rotations, mulching, weed management, water management and intercropping, for specific areas of their fields. Variable rate application PA tools, can be used to apply inputs, such as fertilizers, pesticides, and water, at different rates across a field. This can help farmers to reduce inputs in areas where they are not needed and increase inputs in areas where they are needed, which can help to improve crop yields, reduce costs and improve input use efficiency. The recent advancement in robotics and autonomous vehicles-based PA tools can be used to automate tasks such as planting, nutrient and pesticide application, harvesting, and weed control, which can help to reduce labor costs and improve efficiency. Further, crop modeling tools can be used to simulate crop growth and predict nutrient requirements, crop yields under different management scenarios. The objective of this paper is to evaluate the potential use of Precision Agriculture principles and technology for Conservation Agriculture. Examples of Precision Agriculture application through the integration of various techniques are presented to show the potential benefits of site-specific nutrient management. Further perspectives are also discussed to link Precision Agriculture to Conservation Agriculture for higher nutrient use efficiencies.

Key words: Conservation agriculture, precision agriculture, natural resources nutrient use efficiency, sustainability

Introduction

Conservation agriculture (CA) is a modern approach to farming that promotes the sustainable use of natural resources by application of modified crop management practices such as minimal soil disturbance, maintaining a permanent soil cover, and diversifying crop rotations. The benefits of CA include improved soil health, increased crop yields, reduced erosion and runoff, improved water retention, carbon sequestration and climate change mitigation. CA can also help to increase biodiversity and reduce the need for synthetic fertilizers and pesticides. Overall, CA is a holistic approach to farming that can help farmers to achieve greater sustainability and resilience in their farm operations. On the other hand, precision agriculture (PA) is a comprehensive system designed to optimize agricultural production with high input use efficiency through the application of crop information, soil variability, state of the art technology and management practices. It promotes adoption of farming method that uses technology to optimize crop production and reduce input requirements such as seeds, fertilizers, and pesticides through need based optimal allocation of resources. The scope of PA includes the use of precision farming tools such as GPS, GIS, remote sensing, and precision farming software's. These tools allow users to collect and analyze data on crop growth, weather, soil conditions, and other factors, which can be used to make more informed decisions about sowing, fertilizer application, and harvesting crops. Understanding soil variability by using state-of-the-art techniques at field and series level is of utmost important as large differences exist in the topography, slope, and management practices followed by individual farmers is a key component of precision agriculture.

Application of PA technologies will not only help in increasing crop yields, reduced input costs, improved water and nutrient management, but will also help in reducing the environmental impact of conventional agriculture. PA can help farmers to manage resources such as water and fertilizer in a better way, which can help in improving sustainability and resilience of agriculture in the era of climate change by helping to make more informed decisions about crop management, which can lead to greater efficiency, higher yields, and reduced environmental impact. Additionally, PA can also help users to identify and address the issues such as disease, pests, and soil variability more quickly, which can lead to increased efficiency and profitability. A careful integration of these technologies will be further helpful in standardization of sustainable farming methods that help farmers to optimize crop production and reduce inputs, resulting in greater profitability and resilience. Thus, CA and PA are modern farming methods that aim to improve crop yields and reduce the need for external inputs. However, they have slightly different approaches and focus, with CA emphasizing minimal soil disturbance, maintaining soil cover, and diversifying crop rotations with low environmental foot prints, while PA focuses on using technology and data to optimize crop management practices. Therefore, huge opportunities for integration of CA and PA technologies as the core aim of both the technologies are optimal allocation of resources, achieving higher input use efficiency and conservation. PA tools, such as precision mapping, soil sensors, and yield monitors, can be used to gather data on soil conditions, crop growth, and other factors that can then be used to make site-specific nutrient management decisions. This can help farmers to optimize CA practices, such as nutrient application, crop rotations, mulching, weed management, water management and intercropping, for specific areas of their fields. Variable rate application PA tools, can be used to apply inputs, such as fertilizers, pesticides, and water, at different rates across a field. This can help farmers to reduce inputs in areas where they are not needed and increase inputs in areas where they are needed, which can help to improve crop yields, reduce costs and improve input use efficiency. The recent advancement in robotics and autonomous vehicles-based PA tools can be used to automate tasks such as planting, nutrient and pesticide application, harvesting, and weed control, which can help to reduce labor costs and improve efficiency. Further, crop modeling tools can be used to simulate crop growth and predict nutrient requirements, crop yields under different management scenarios. This can help farmers to optimize CA practices, such as nutrient management, crop rotations, mulching, and intercropping, for specific areas of their fields.

Nutrient Management

Nutrient management is the process of managing the amount, form, and timing of nutrient application to crops in order to optimize crop growth and yields while minimizing negative environmental impacts. Conservation Agriculture through its basic principles can help in improving soil health and can help in reducing the nutrient requirement through improving and maintaining soil health by reducing soil erosion, crop residue retention and increasing soil organic matter. Healthy soils rich in organic matter can hold more nutrients and water and thus can help in improving nutrient use efficiencies. This can be further benefitted through inclusion of modern techniques such as precision agriculture, soil testing, and data management. By using precision agriculture techniques, farmers can apply fertilizer, pesticides, and other inputs in a targeted and precise manner, which can help to reduce waste and environmental impact while increasing efficiency and yields. Precision agriculture tools will help in efficient use of fertilizers and other inputs to optimize crop growth and yields while minimizing negative environmental impacts. Precision agriculture can help the farmers to collect data on their fields, such as soil maps, yield maps, weather data, and crop growth data, which can be used to make informed decisions about nutrient management. Precision agriculture tools can also be used to help farmers make more precise nutrient application, such as variable-rate application of fertilizers, which can help to optimize the use of inputs, reduce costs, and minimize environmental impacts.

Nutrient use efficiency refers to the ability of a plant or crop to effectively utilize the nutrients in the soil for growth and development. It is typically measured as the ratio of the amount of a nutrient absorbed by the plant to the amount of that nutrient applied to the soil. Improving nutrient use efficiency can lead to increased crop yields and reduced environmental impact by reducing the amount of fertilizer or other nutrients needed to produce a given amount of food. This can be achieved through genetic modifications, agronomic practices, and the use of soil amendments. Nutrient use efficiency varies for different nutrients in agricultural fields based on soil, plant and atmospheric interactions. Some common nutrients that are important for plant growth and development include.

Nitrogen: Nitrogen is an essential nutrient for plant growth, and it is often the nutrient that is most limiting to crop yields. Nitrogen use efficiency is typically low (30-40%), as a significant amount of applied nitrogen is lost to the environment through leaching or volatilization.

Phosphorus: Phosphorus is another essential nutrient that is important for plant growth. Phosphorus use efficiency (15-20%) is often lower than nitrogen use efficiency, as phosphorus is less mobile in the soil and can be less available to plants.

Potassium: Potassium is a key nutrient for plant growth and development, particularly for root development and stress tolerance. Potassium use efficiency (50-70%) is generally considered to be high, as plants are able to take up and use much of the potassium that is applied to the soil.

Sulfur: Sulfur is an essential nutrient that is important for protein synthesis and the development of plant tissues. Sulfur use efficiency is generally considered to be low, for cereal crops (15-20%). This low SUE may be attributed to S leaching from the soil profile, immobilization, retention in residues, and adsorption.

Micronutrients: Micronutrients such as zinc, iron, and copper are also essential for plant growth, but they are required in much smaller quantities than macronutrients. Micronutrient use efficiency can vary depending on the specific nutrient the crop being grown and soil conditions.

It's worth noting that the nutrient use efficiency can be affected by various environmental factors such as soil type, temperature, moisture, crop type, and management practices. There are several ways to improve nutrient use efficiency in plants and crops viz. genetic modification, agronomic practices, application of soil amendments, biological methods by using microorganisms such as rhizobia and mycorrhiza, use of slow-release fertilizers, Intercropping and use of precision agriculture technologies such as sensor-based nutrient management, variable rate application, Site-specific management, Robotics and autonomous vehicles, Crop modeling and precision irrigation can also help to improve nutrient use efficiency.

Nutrient Management in CA

Nutrient management is an important aspect of conservation agriculture because it helps to maintain soil fertility and improve crop productivity. The aim of nutrient management is to maintain soil nutrient levels, replenishing the losses resulting from the nutrients absorbed by the crops and minimizing adverse impact on the environmental quality. In conservation agriculture, nutrient management focuses on using natural processes and inputs to supply plants with the necessary nutrients for growth. Managing nutrient application in conservation agriculture involves a combination of practices that help to maintain soil fertility and improve crop productivity. Results of long-term conservation agriculture experiments world over, which includes practices such as reduced tillage, crop rotation, and cover cropping, were found to have significant positive long-term effects on soil health and nutrient dynamics. Reduced tillage can help to conserve soil moisture and organic matter, which can improve soil health and fertility over time and thus significant amount of crop nutrients which otherwise were lost can be saved through insitu retention of crop residues in the field. Crop rotation can also help to improve soil health by adding diversity to the cropping system and breaking pest and disease cycles. Cover cropping can help to add organic matter to the soil and improve soil structure, as well as reduce erosion and runoff. Additionally, conservation agriculture can help to reduce the need for chemical fertilizers by building soil health and fertility. In this way, conservation agriculture can lead to sustainable nutrient management in the long-term. Nutrient management is more complex with CA because of higher residue levels at soil surface and reduced options with regard to method and timing of nutrient applications compared to CT systems. Kassam and Friedrich (2009) suggested that nutrient management strategies in CA systems would need to be developed based on the general aspects: i) Improvement in soil organic matter and the soil quality (physical, chemical and biological properties of the soil); ii) Improved soil nutrient stocks through residue recycling and biological nitrogen fixation (when legumes are included) to meet crop needs; and iii) the soil acidity/alkalinity is kept within acceptable range for all key soil chemical and biological processes to function effectively.

5R-Nutrient Stewardship

The 5R-Nutrient Stewardship is an innovative approach centered on five key areas of nutrient management; right rate, right source, right place, right time and right combination, for precise fertilizer practice which considers NUE, economic and environmental dimensions of fertilizer management that are important for sustainability of agricultural systems. Managing the 5R- is best accomplished with the right tools for crop-location specific N-management practices. A key scientific principle to select the right fertilizer rate is matching nutrient supply with plant nutrient demand throughout the growing season to avoid nutrient deficiency or excess. Results from a long-term study on CA-based practices in R-W and M-W systems showed that to achieve similar yields, wheat required 30% less fertilizer N and 50% less fertilizer K compared to CT-R-W system with similar management practices (Jat *et al.*, 2018a). Under residue retention in CA, the 100% basal application of coated fertilizer like neem and sulphur coated urea found effective for enhancing NUE and water productivity with INR 3000 to 4000 ha^{-1} more net return compared to conventional split application of prilled urea in MW system (Jat *et al.*, 2014).

The losses of N may be minimized by either drilling the fertilizer into the soil below the surface residue, applying N just prior to a rain or irrigating after fertilizer application, and/or by delaying the application of N fertilizer when a significant portion of residues have undergone decomposition. Sub-surface banding of P and K with the seed or ideally about 6-10 cm below the seed is highly recommended to promote deeper root growth and avoid stranding these nutrients near the soil surface under the CA system. Similarly, surface application of urea and urea-containing fertilizers results into severe loss of N under ZT system, particularly at the early phases of crop establishment when there is ample moisture and substantial amount of undecomposed organic substrate at the surface of the soil. The subsurface drilling reduces ammonia volatilization losses. Grahmann *et al*. (2016) reported that broadcast fertilizer application compared with drilling of N in between rows of wheat reduced grain yield and N use efficiency. They concluded that N fertilizer management in furrow-irrigated wheat cropping systems should combine splitting the N dose and disking it on the bed pre-planting and in the furrow later in the season, depending on the crop needs at the application time. Results from a two-year study from north-west India showed a saving of 30 kg N ha^{-1} in both maize and wheat with the deep placement of N fertilizer on permanent raised beds compared to uniform broadcast using recommended rate of 120 kg N ha^{-1} to get similar grain yields (Sandhu *et al.*, 2019). N use efficiency was significantly higher with deep placement of urea on beds in both wheat and maize compared with broadcast application. Majeed *et al.* (2015) showed that in wheat planting on permanent beds, N application at 120 kg ha^{-1} produced 15% higher grain yield, and 30% higher N use efficiency than flat planting at the same N rate. Planting of wheat on beds with application of 80 kg N ha^{-1} gave yield similar to that of flat planting with 120 kg N ha^{-1}. Nitrogen deep placement in ZT dry seeded rice significantly decreased NH_3 volatilization by 15–45% and increased N recovery efficiency by 26–93% compared with N broadcasting (Liu *et al.*, 2015). Split applications of N during the growing season, rather than a single, large application prior to planting, are known to be effective in increasing NUE. The new plant-based diagnostic tools such as chlorophyll meter (SPAD), leaf colour chart (LCC) and GreenSeeker (GS) optical sensor can help in-season estimation of the right time and rate of N application matching the uptake requirement of a crop in a site-specific manner.

Nutrient dynamics and availability under CA

Nutrient dynamics and availability can be positively impacted by the use of conservation agriculture practices. The permanent soil cover provided by crop residues or cover crops can help to reduce nutrient loss through erosion and improve soil organic matter, which in turn can improve nutrient retention and availability. Crop rotation can also help to improve nutrient availability by providing different crops with different nutrient requirements, which can help to balance nutrient uptake and reduce the need for synthetic fertilizers (Jat *et al.*, 2020). Compared to incorporated crop residues, surface residues in ZT decompose at a much slower rate (Yadvinder-Singh *et al.*, 2010). The development of continuous pores between the surface and subsurface (causing high infiltration rate) under CA may lead to more rapid passage of soluble nutrients (e.g. NO_3) deeper into the soil profile than when soil is tilled (Turpin *et al.*, 1998). A combination of high C:N ratio of cereal residues and low soil N is expected to reduce N availability to plants due to immobilization at the initial phases of crop growth and may decline grain yields, particularly during the initial 2-3 years of adoption of CA (Dordas, 2015; Verhulst *et al.*, 2010) and in few cases additional applications of N fertilizer may be required to maintain yield (O'Leary and Connor, 1997). In the years following the adoption of CA, soil microorganisms will significantly increase the N mineralization leading to less need for N fertilizers over time. The improvements in SOC observed in CA systems will have a significant effect on plant nutrient availability due to both changes to the quantity of nutrients available, and their distribution in the soil profile (Jat *et al.*, 2020). Continuous addition of crop residues in CA leads to greater input of plant nutrients in soil, resulting in increased storage and availability of macronutrient (Choudhary *et al.*, 2018a; Choudhary *et al.*, 2020; Nandan *et al.*, 2019; Parihar *et al.*, 2020a; Thind *et al.*, 2019; Yadvinder-Singh *et al.*, 2014b; Jat *et al.*, 2018a, 2019d; Das *et al.*, 2020) and micronutrients (Jat *et al.*, 2018a; Nandan *et al.*, 2019; Gupta *et al.*, 2007; Zahid *et al.*, 2020).

From a long-term study in the IGP of north-west India, Jat *et al.* (2018a) recorded significantly higher available N, P, K, Zn, and Mn contents at 0-15 cm depth under CA based agricultural practices. DTPA-extractable (available) Zn concentrations were 51% and 93% higher under CA-based maize-wheat (MW) and rice-wheat (RW) systems compared to CT-RW system, respectively. The build-up of SOC and increases in nutrient availability suggest that, in long–term, the dose of mineral fertilizers may be reduced in CA systems (Thuy *et al.*, 2008; Yadvinder-Singh *et al.*, 2009).

Site-Specific Nutrient Management (SSNM)

Traditionally, fertilizers are applied uniformly across large area while ignoring inherent spatial variation in crop needs within crop fields. This often results in either reduced yields or low NUE. Site-specific nutrient management (SSNM) is a farming practice that uses precision agriculture techniques to determine the specific nutrient needs of different areas of a field, rather than applying the same amount of nutrients to the entire field. This approach can help farmers optimize crop yields, reduce costs, and minimize environmental impacts. Techniques used in SSNM include soil testing, yield mapping, and remote sensing. The specific nutrients, such as Nitrogen, Phosphorus and Potassium, are applied based on the crop requirement, soil type and weather conditions to maximize the crop yield. SSNM is based on a set of nutrient management principles (crop removal adjusting the soil residual nutrients), which aims to supply a crop's nutrient requirements tailored to a speciûc ûeld or growing environment. Major technologies focused on the adoption of modern diagnostic tools for SSNM for effectively enhancing the NUE, economic profitability with lower environmental footprints include use of SPAD, LCC, GS and Nutrient Expert® (NE) under both CT and CA systems. The plant-based diagnostic tools provide a valuable estimation of the N status of the crop and develop precision N management practices (Bijay-Singh *et al.*, 2020). These tools helped in-season estimation of the right time and rate of N application matching the uptake requirement of rice, wheat and maize in a site-specific manner. The SSNM approach does not necessarily aim to either reduce or increase fertilizer use. Instead, it aims to recommend nutrients at optimal rates and times to achieve higher profit for farmers, with higher efficiency of nutrient use by crops across spatial and temporal scale, thereby preventing leakage of excess nutrient to the environment. Some of the SSNM tools that can help in making smart nutrient management decisions includes use of SPAD meter or LCC which can reduce N requirement from 12-25% with no loss in yield in RW system of IGP. The results of GS sensor-based N management resulted into similar (in rice) to higher yield (in wheat) with 10-20% lower N rates compared recommended practice thereby increasing NUE. The precision nutrient prescriptions using SSNM based decision support tools offers a new management paradigm for scaling up of the CA-based cropping systems in India and other countries of South Asia. Nutrient Expert® (NE), an interactive decision support system based nutrient application recorded better efficiency of nutrients than in farmers' practice indicates that location-specific nutrient application rate and better timing of nutrient application (i.e. a greater number of splits and matching physiological demand of the crops) reduced N losses and enhanced efficiency of nutrient utilization.

Fertigation with drip irrigation systems for increasing nutrient use efficiency

Integrating CA, decision tools/sensors and fertigation can boost the NUE significantly. Field experiment conducted at BISA, Ladhowal, Punjab showed that fertigation using SDI in in CA-based RW system significantly increased N use efficiency in both rice and wheat compared to both flood irrigated ZT and CT (Sidhu *et al*., 2019). Results from another study by Jat *et al*. (2019c) showed that SDI system resulted in 25% saving of fertilized N in rice, maize and wheat without any yield penalty. On system basis SDI system saved 47 and 45% irrigation water under CA-based RW-mungbean and MW-mungbean systems compared to their respective flood irrigated CA-based systems (C.M. Parihar, personal communication). Fertigation increased N use efficiency by about 47% compared with farmer's practice of flood irrigation. Above-mentioned these studies showed that SDI system provided tangible benefits for substantial saving in irrigation water and energy and increasing NUE and net income for CA-based RW and MW systems in NW India.

Mechanization for precision N application in CA

This approach emphasizes the use of minimal tillage, permanent soil cover, and crop rotation to improve soil health, reduce erosion, and conserve natural resources through mechanization for precision nitrogen (N) application in Conservation Agriculture (CA) by using specialized equipment and technology to apply nitrogen fertilizer to crops in a way that is consistent with the principles of CA. In CA, precision N application can involve the use of GPS-guided tractors and sensors to precisely apply fertilizer at specific rates and locations based on crop needs. This allows farmers to target their fertilizer application to the areas of the field where it is most needed, reducing the overall amount of fertilizer used while still ensuring optimal crop growth and yield. Additionally, precision N application can be integrated with other CA practices such as cover cropping, and intercropping, to optimize soil health and fertility. Overall, the use of mechanization for precision N application in CA can help farmers achieve their agronomic goals while also promoting soil health and conservation of natural resources, which is crucial for sustainable farming practices. Fertilizer N precisely placed in the N near root zone was found to reduce the volatilization losses. After planting, application is usually restricted to N and its placement can be as a top dress or a subsurface side dress. Application of fertilizers in a localized band allows for more efficient use of N and as a result, lower application rates can be used than what would be needed if the urea was broadcast on the surface and not incorporated. In a RW system, fertilizer efficiency increased by 10–15% due to better placement of fertilizer using fertilizer cum seed drill compared with broadcasting in the CT system (Hobbs and Gupta, 2004). With the development of straw management machine called Turbo Happy Seeder (THS), band placement became possible allowing ammonium-based fertilizers like urea to be used effectively (Sidhu *et al*., 2015). With THS, fertilizer P (DAP) and K can be drilled directly through the residues at appropriate depth at 1-2 cm below the seed placement. Study by Yadvinder-Singh *et al*. (2015) showed that better fertilizer N management strategy in terms of achieving higher grain yield and NUE for ZT wheat sown into rice residue was drilling of 24 kg N ha^{-1} as di-ammonium phosphate (DAP) into the soil at seeding followed by two top dressings of 48 kg N ha^{-1} each just prior to first and second irrigations compared to the presently recommended N fertilizer recommendation for CT wheat; applying 60 kg N ha^{-1} at sowing and the remaining 60 kg N ha^{-1} with first post-sowing irrigation. Results from field evaluation of these furrow openers' showed that up to 75% of recommended fertilizer N dose for ZT wheat (120 kg N ha^{-1}) along with P and K fertilizers can be drilled at seeding with significant increase in grain yield over the recommended practice of broadcast application in two equal splits in medium to fine-textured soils. On the coarse-textured soil (sandy loam), drilling more than 50% of the recommended fertilizer N at sowing significantly reduced grain yield and N use efficiency.

Regulating rate and time by nitrogen application for coincide nitrogen availability to crop needs is the best agronomic approach that would result in better synchrony of crop N demand and with the supply of N to crops. Different nutrient-management approaches such as leaf-colour chart (LCC), Nutrient Expert, a computer-based decision support tool (Kumar *et al*., 2016), chlorophyll meter (SPAD meter) etc. are precision tools to increase fertilizer efficiency and productivity of crop. Singh *et al*. (2016) reported that the LCC-treated plots showed higher increase in grain yield/kg N applied over fixed time interval of N treatments. Using of LCC score 3.0 with 90 kg N/ha showed grain-yield equivalent to 120 and 150 kg N/ha applied at fixed time interval and gave higher recovery efficiency to the tune of 12.1–18.1 unit and 4.1–5.1 kg higher grain yield/kg fertilizer N applied, whereas LCC 5.0 resulted in significant higher grain yield.

Similarly, SPAD readings were widely used for fertilizer application in rice crop. Peng *et al.* (1996) reported that yields with SPAD-based management were 93–100% of maximum yields achieved by the best fixed-timing treatment with lower total N rates in SPAD-based N treatments. They further corroborated that increased recovery efficiency from applied N and greater utilization of the acquired N to produce grain contributed to the significantly greater fertilizer-N efficiency of the SPAD-based than of the fixed-timing N treatments.

Green Seeker™, an optical sensor (GS) is emerging as useful tool for site-specific need based N fertilizer management in cereals. It uses normalized difference vegetation index (NDVI) based on reflectance of radiation in the red and near infrared bands. Raun *et al*. (2002) showed that prediction of wheat response to N applications guided by optical sensor was positively correlated to measured N response and increased nitrogen use efficiency. Raun *et al*. (2005) further refined the N application algorithm using the coefficient of variation from NDVI readings. Ali *et al.* (2014) reported that measurements made with optical sensor at panicle initiation stage of direct seeded rice could satisfactorily predict the grain yield at maturity.

Conclusion

Precision farming includes precise micro-management of every step of the farming process. It allows the farmer to produce more efficiently, thereby realizing gains through economical and efficient use of resources. Precision agriculture tools can help to optimize nutrient application in conservation agriculture by providing detailed information about the specific nutrient needs of the crops. This can help farmers to apply the right amount of nutrients at the right time and in the right place, leading to improved crop yields and reduced input costs under CA.

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Precise Assessment and Management of Soil Health- A Key to Sustainable Intensification of Agricultural Production

K.K. Bandyopadhyay[1] and Bappa Das[2]

[1]*Indian Agricultural Research Institute, New Delhi*
[2]*Central Coastal Agricultural Research Institute, Goa*

1. Introduction

The health of a nation depends on the health of its soil. The importance of soils to humankind is documented by the many ancient civilizations, some of which vanished or collapsed because of mismanagement the soils on which they depended (Wienhold *et al.*, 2006; Diamond, 2005; Lal, 2006). Agricultural sustainability depends to a large extent upon the maintenance or enhancement of soil health/quality. Soil quality cannot be directly measured from the soil alone but can be inferred from soil characteristics and soil behaviour under defined conditions, while certain soil quality characteristics are found to be potential indicators of soil health. Over-exploitation of soils over the decades has resulted in fatigue in the intensive agricultural production systems worldwide with a steadily declining trend in productivity, witnessed in such systems (Nambiar *et al.*, 2001). Soil quality is conceptualized as the major linkage between the strategies of conservation management practices and achievement of the major goals of sustainable agriculture (Acton and Gregorich, 1995; Parr *et al.*, 1992). Thus, the land care and soil quality management assume great significance for ensuring agricultural sustainability which is inevitable to feed the burgeoning population, not only in India, but across the world.

1.1 Soil quality degradation and the need for periodic assessment

Past management of agricultural and terrestrial ecosystems to meet the needs of increasing human population has taxed the capacity and resilience of soil and ecosystem functions to maintain the global balance of energy and matter (Doran and Parkin, 1994; Amezketa, 1999; Doran, 1999; Moebius *et al.*, 2007). Worldwide deforestation, overgrazing, and conversion of rangelands have resulted in a great decline in the physical, chemical, and biological quality of soil resources (Doran *et al.*, 1998). Therefore, many soils have been worn down to their nadir for most soil parameters essential for effective, stable and sustainable crop production (Moebius, 2007; Govaerts *et al.*, 2008b; Kibblewhite *et al.*, 2008). In consequence, soil degradation or decline in soil quality (SQ) is emerging as an environmental, economic and policy issue of increasing global trend (Eswaran *et al.*, 2005; Liu, 2006; Montgomery, 2007; Hartemink, 2008; Hartemink and McBratney, 2008; Cécillona, 2009). Soil degradation refers to the decline in soil's inherent capacity to produce economic goods and perform its ecologic functions including environmental protection as a result of natural or human activities (UNEP, 1993). Globally it affects 2 billion ha area (UN, 2000), while in India, 120.72 million ha (Mha) out of 328.73 Mha of the land area is degraded in one way or the other (ICAR and NAAS, 2010) (Table 1).

Table 1. Land degradation statistics of India

Degradation type	Arable land (M ha)	Open forest (<40% canopy) (M ha)	Data source
Water erosion (>10 tonnes/ha/yr)	73.27	9.30	Soil Loss Map of India–CSWCR&TI
Wind erosion (Aeolian)	12.40	–	Wind Erosion Map of India–CAZRI
Sub-total	85.67	9.30	
Chemical degradation			
Exclusively salt-affected soils	5.44	–	Salt-Affected Soils Map of India, CSSRI, NBSS&LUP, NRSA and others
Salt-affected and water eroded soils	1.20	0.10	
Exclusively acidic soils (*p*H< 5.5)#	5.09	–	Acid Soil Map of India NBSS&LUP
Acidic (*p*H < 5.5) and water eroded soils #	5.72	7.13	
Sub-total	17.45	7.23	
Physical degradation			
Mining and industrial waste	0.19		Wasteland Map of India–NRSA
Waterlogging (permanent surface inundation)$	0.88		
Sub-total	1.07		
Total	104.19	16.53	
Grand total (Arable land and open forest)	120.72		

Notes: Forest Survey of India Map (1999) was used to exclude degraded land under dense forest; Unculturable Wastelands: Barren rocky/stony waste: 6 M ha, are the source for runoff water and building material; Snow covered/Ice-caps: 6 M ha, are best source of water and are not treated as wastelands.
\# For acid soils, areas under paddy growing and plantation crops were also included in the total acid soils
$ Sub-surface waterlogging not considered.
Source: NBSS&LUP

A landmark 1991 United Nation study estimated that soil in 552 million hectares of land, equal to 38% of today's global cultivated area, had been degraded to some degree by agricultural mismanagement since World War II (Gardner, 1997). It is estimated that the soil in 11% of the vegetative area and 38% of the cultivated area in the world are degraded (Hammond, 1992; Gardiner and Miller, 2004; Liu, 2006). Approximately 24 billion tons of topsoil is lost annually, which is equivalent to about 9.6 million hectares of land (Bakker, 1990). The rate of growth of global grain production dropped from 3% in the 1970s to 1.3% in the 1983–1993 period, and one of the key reasons of this decline is poor soil and water management (Steer, 1998). It is heartening to note that India is now conscious of soil degradation and is attempting to have a Soil Degradation Neutral India by 2030 in line with the United Nations Convention to Combat Desertification (UNCCD) goal of land degradation neutrality in the world by 2030. Therefore there is a need for regular assessment and management of soil health to improve agricultural productivity to feed the growing population.

1.2. What is Soil Quality/ Soil Health?

Conceptual definitions of soil quality are still evolving and present definitions of soil quality vary depending on the views and the background of individuals. Traditionally, soil quality was equated with various soil properties that contribute to soil productivity, which is the capacity of a soil to produce a single crop or sequence of crops under a given management systems.

Larson and Pierce (1994) defined soil quality "as the capacity of a soil to function within its ecosystem boundaries and interact positively with the environment external to that ecosystem". This definition also recognizes that soil serves other functions both within and beyond agricultural ecosystems. A more detailed definition has been developed by the Soil Science Society of America (1995) as follows: "Soil quality is the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation". This definition is similar to that of Doran *et al*. (1996) where soil quality is the "capacity of a soil to function, within ecosystem and land use boundaries, to sustain biological productivity, maintain environmental quality, and promote plant, animal and human health".

The concept of soil quality is closely related to that of soil health, which is widely used within discussions on sustainable agriculture to describe the general condition or quality of the soil resource. For instance, Kibblewhite *et al*. (2008) proposed a definition of soil health as follows: that a healthy agricultural soil is one that is capable of supporting the production of food and fibre, to a level and with a quality sufficient to meet human requirements, together with continued delivery of other ecosystem services that are essential for maintenance of the quality of life for humans and the conservation of biodiversity'. Soil health is defined as the continued capacity of soil to function as a vital living system, by recognizing that it contains biological elements that are key to ecosystem function within land-use boundaries (Doran and Zeiss, 2000; Karlen *et al*., 2001). These functions are able to sustain biological productivity of soil, maintain the quality of surrounding air and water environments, as well as promote plant, animal, and human health (Doran *et al*., 1996). Idowu *et al*.

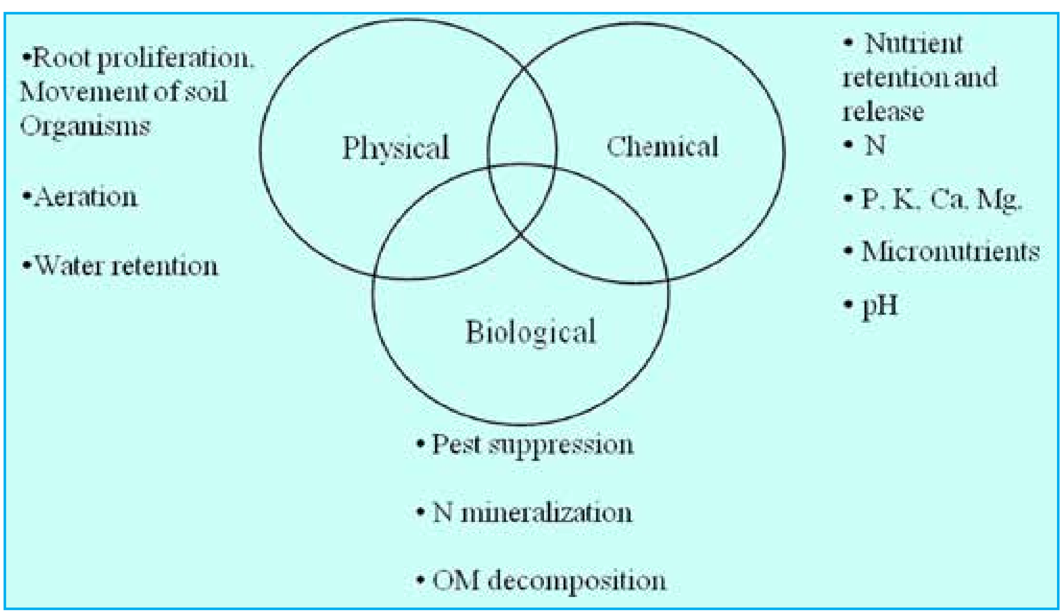


Figure 1. Soil physical, chemical and biological processes and functions

(2007) remarked that the term "soil quality" is more favored by scientists, whereas "soil health" is a term favored by farmers as it connotes a holistic approach to soil management. Soil quality is related to soil function (Karlen *et al.*, 2003; Letey *et al.*, 2003), whereas soil health presents the soil as a finite non-renewable and dynamic living resource (Doran andZeiss, 2000). It has been depicted in Fig. 1 that soil health is a composite picture of the state of the soil's physical, chemical and biological properties. The quantity and quality of soil organic carbon influences the physical, chemical and biological soil quality indicators. Therefore an important issue in soil quality/health is the integration of the chemical, biological and physical processes and functions (Dexter, 2004; Idowu *et al.*, 2007; 2008).

Daily *et al*. (1997) described six functions performed by soil for the larger agroecosystem as: (1) buffering and moderation of the hydrological cycle, (2) physical support of plants, (3) retention and delivery of nutrients to plants, (4) disposal of wastes and dead organic matter, (5) renewal of soil fertility, and (6) regulation of major element cycles. Karlen *et al*., (1997) propose five vital soil functions which include (1) sustaining biological activity, diversity, and productivity; (2) regulating and partitioning of water and solute flow; (3) filtering, buffering, degrading, immobilizing, and detoxifying organic and inorganic materials, including industrial and municipal byproducts atmospheric deposition; (4) storing and cycling of nutrients and other elements within the Earth's biosphere; and (5) providing support of socioeconomic structures and protection for archeological treasures associated with human habitation .

These soil functions are related to different soil physical, chemical and biological indicators (Seybold, 1997) (Fig. 2).

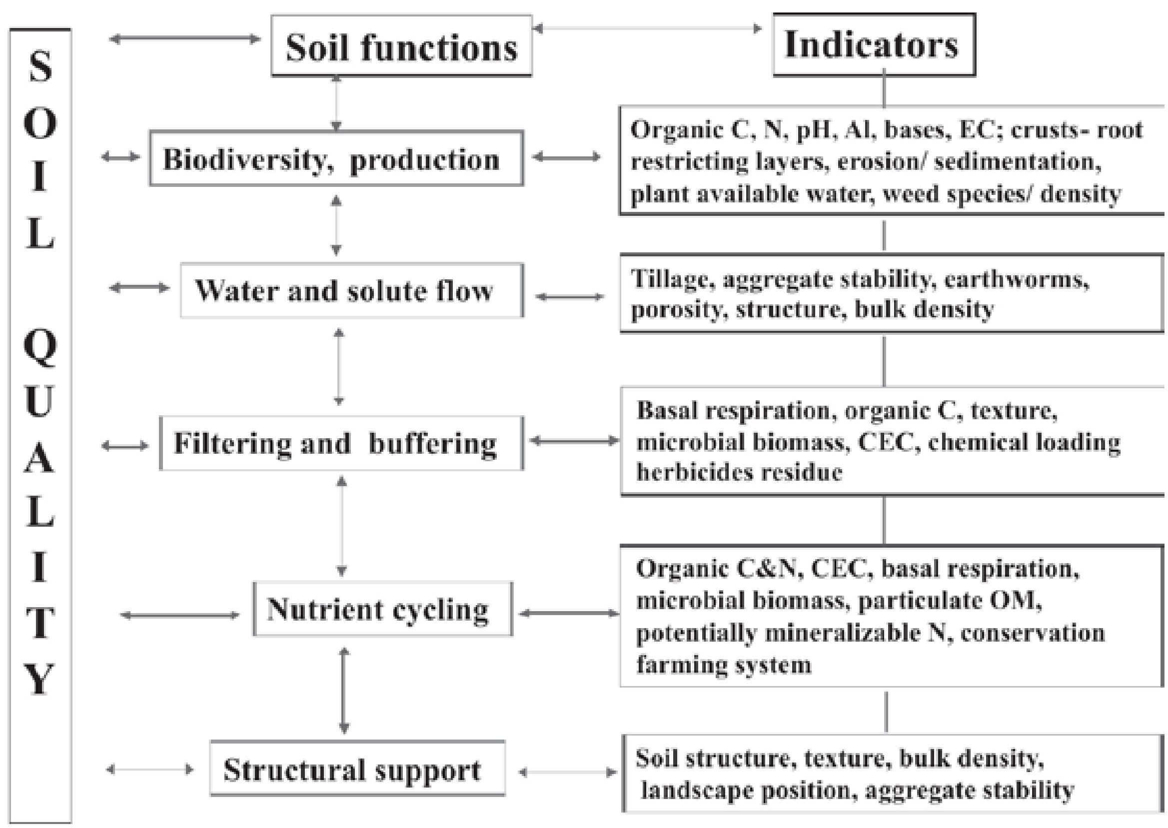


Figure 2. Graphical representation of the concept of soil quality (Source: Seybold *et al.*, 1997)

2. Potential Soil Quality Indicators

One of the most prevalent soil quality research theme focuses on indicator selection and evaluation (Karlen *et al*., 1992; Brejda *et al*., 2000a, b; Islam and Weil, 2000; Rezaei *et al*., 2006). Soil quality cannot be measured directly, but soil properties that are sensitive to changes in management can be used as indicators (Brejda *et al*., 2000a). Soil quality indicators are either inherent or dynamic (Fig. 3). Inherent indicators are determined by the soil forming factors of climate, parent material, time, topography, and biota (Jenny, 1941). Inherent soil properties and interpretation of how they affect potential land use are the foundation for soil survey, classification, and land use recommendations (Oluwatosin *et al*., 2006). However, dynamic indicators describe the condition of the soil due to land use or management decisions. Dynamic indicators are used to assess how soil management decisions affect use-dependent soil properties.

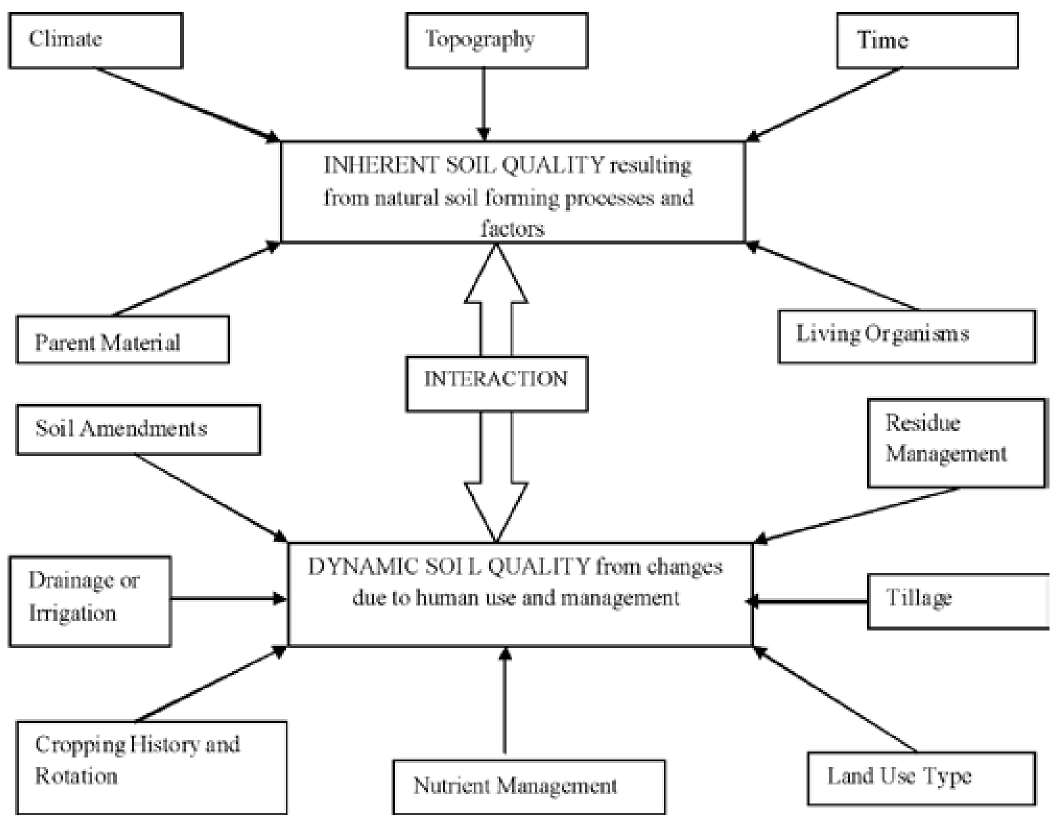


Figure 3. Inherent and dynamic soil quality indicators

It is practically impossible to evaluate soil quality in terms of all soil attributes (Giuffre, 2006). Using a minimum data set (MDS) of soil attributes reduces the need for determining a large number of indicators to assess soil quality (Rezaei *et al*., 2006). To identify the smallest number of measurable soil properties that define the major processes functioning in soil, several MDS have been proposed (Larson and Pierce, 1991; Doran and Parkin, 1996; Arshad and Martin, 2002). These physical, chemical and biological properties could be considered the minimum data set that can be used to assess changes in soil quality (Larson and Pierce, 1991, 1994).

They suggested that standardized methodologies and procedures for assessing changes in soil quality should be established and that reference levels are needed to determine whether a soil is being degraded, maintained or improved. The reference could either be an earlier data set from the same soil, modal data for the soil, or comparison to data from the same soil in native conditions.

Larson and Pierce (1994) also suggested that soil properties that are too costly or difficult to measure but would be desirable parameters for soil quality assessment could be predicted from other soil properties using pedotransfer functions (Bouma, 1994). The pedotransfer function is a mathematical function that relates a given soil property with other, more simply measured, properties for use in evaluations of soil quality (Larson and Pierce, 1991). Phosphate-sorption capacity, cation exchange capacity, bulk density, water retention, porosity, hydraulic conductivity, electrical conductivity saturated conductivity, soil productivity, and rooting depth are some of soil properties for which pedotransfer functions have been proposed for. A similar proposal was made by Doran and Parkin (1994) who added cation exchange capacity, and aggregate stability to the pedotransfer indicators listed above. Cation exchange capacity, for example can be estimated from soil organic matter, pH and clay content. Doran and Parkin (1994) emphasized that the listed properties are only basic for initial characterization of soil quality and that other sets of properties may be needed as dictated by existing data bank, climatic, geographic, and socio-economic conditions or as indicated by assessment of the basic indicators.

Arshad and Martin (2002) proposed a set of soil quality indicators that include organic matter, topsoil depth, infiltration, aggregation, pH, electrical conductivity, suspected pollutants, and soil respiration. Crop yield is to be used as an integrator of these indicators. These authors stated that a minimum data set must be established for each indicator, and that monitoring must take place that reduces the influence of soil heterogeneity, seasonal fluctuations, and analytical uncertainties. These authors set out guidelines to identify critical limits for key indicators and a procedure for monitoring changes in soil quality trend.

The soil quality indicators used or selected by different researchers in different regions may not be the same because soil quality assessment is purpose and site-specific (Wang and Gong, 1998; Shukla *et al*., 2006). However, while selecting the indicators, it is important to ensure that the indicators should i) correlate well with natural processes in the ecosystem (this also increases their utility in process-oriented modelling), ii) integrate soil physical, chemical, and biological properties and processes, and serve as basic inputs needed for estimation of soil properties or functions which are more difficult to measure directly, iii) be relatively easy to use under field conditions, so that both specialists and producers can use them to assess soil quality, iv) be sensitive to variations in management and climate, and v) be the components of the existing soil databases wherever possible (Doran *et al*., 1996; Doran and Parkin, 1996).

3. Diagnostic Tools for Soil Quality Assessment

Worldwide, protocols to monitor air and water quality have been standardized and widely adopted (Riley, 2001). In contrast, assessment of soil quality across agricultural systems, soil types and climatic zones presents major scientific and policy challenges. Although an estimated 65% of the land area worldwide is degraded (FAO, 2005), no standardized SQ tests exist currently, especially for use in the tropics (Moebius, 2007). Given the multicomponent nature of soil systems, the breadth of services and functions that they are called upon to provide, and their spatial variability, a complex debate is to be expected about appropriate methods for soil assessment. The World Soils Agenda developed by the International Union of Soil Scientists lists as the first two agenda items 1) assessment of status and trends of soil degradation at the global scale and 2) definition of impact, indicators and tools for monitoring and evaluation (Hurni *et al.*, 2006). There is clearly a need for international standards to measure SQ. These could be useful for agricultural research and extension agencies, non-governmental organizations, governments and farmers to better understand, implement and monitor sustainable soil management practices (Moebius, 2007). This section reviews the various tools that have been most limiting parameter(s).

3.1 Dynamic assessment

Larson and Pierce (1991) proposed that soil quality (Q) can be expressed as a function of attributes of soil quality (qi) defined as

$Q= f (q_i,........,q_n)$

soil quality index (SQL) is used to represent Q

$$\frac{dQ}{dt} = f\frac{\left(\frac{q_{it}-q_{io}}{q_{io}}, \ldots\ldots, \frac{q_{nt}-q_{no}}{q_{no}}\right)}{dt}$$

where, dQ/dt = dynamic change, t_o = initial time, t = later time when q is measured

A positive value for dQ/dt represents improved soil quality and a negative value for dQ/dt represents declined soil quality or soil degradation

3.2 Regression analysis

Multiple linear regression can be used to calculate soil quality index of crop productivity (Mohanty *et al.*, 2007) using soil attributes as

$Y= a + b_1X_1 + b_2X_2 + ...+ b_nX_n$

where, Y is the crop yield; X_1, X_2, ..., X_n are different soil properties; and a, b_1, b_2, ..., b_n are coefficients of soil attributes.

The actual value of soil attributes and crop yield are normalized as X_i by the relation

$$X_i = \frac{\text{(Observed value of the soil attributes or crop yield } (X_o))}{\text{(Maximum value of the soil attributes or crop yield } (X_m))}$$

X_i may be taken as 1 for the values of X_o exceeding X_m.

The normalized values of the selected soil properties are individually subjected to regression with normalized crop yield to determine their coefficient of determination (R^2)

The proportion of R^2 variation $\left(A_i = \frac{R^2}{\sum R^2}\right)$ obtained was used to calculate weight each soil property score.

Soil quality index (SQI) can be calculated as

$$SQI = \sum_{i=1}^{n} A_i \times X_i$$

3.3 Principal Component Analysis (PCA)

The principle component analysis (PCA) is a useful multivariate statistical tool that has the advantage of generating relationships among many correlated variables into a few principle components (PCs). Principal components (PC) for a dataset are defined as linear combinations of variables that account for maximum variance within the set by describing vectors of closet fit to the *n* observation in *p*-dimensional space, subject to being orthogonal to one another. The objective of PCA is to reduce the dimensionality of the parameter dataset and to identify new meaningful underlying variables, knowing that the PC are dependent on the units used to measure the original variables as well as on the range of values they assume. The first PC accounts for as much of the variability in the data as possible, and each succeeding component accounts for as much of the remaining variability as possible. These can be classified as soil quality indicators with respect to the specific soil functions. Changes in the properties or soil attributes associated with a PC can be used to classify soil quality as aggrading, degrading or stable. In this method, following steps are followed (Andrews *et al*., 2002a,b; Andrews *et al*., 2004): (i) fixing or defining the goals, (ii) testing the level of significance for various soil indicators as influenced by various management treatments, (iii) PCA to select representative minimum dataset (MDS), (iv) correlation analysis among soil variables to reduce spurious grouping among highly weighted variables within each PC, (v) multiple regression using the final MDS components as the independent variables and each goal attribute as a dependent variable, and (vii) scoring of the MDS indicators based on their performance of soil function and computation of SQI.

The minimum data set (MDS) were normalize to 0-1 scale through linear scoring function following Sharma *et al*. (2008), based on their effect on the goal whether 'more is better' or 'less is better' or 'optimum is better'.

After transformation, the SQI value is calculated by summing the multiplication of the weightage of the MDS variables (Wi) obtained through PCA with the score (Si) of that variables obtained through normalization.

$$SQI = \sum_{i=1}^{n} Wi * Si$$

Here, it is assumed that a higher SQI value would indicate greater soil quality and better performance of soil functions.

4. Some Methodological Challenges in Soil Quality Assessment for Management of Tropical Soil Resources

Soil quality assessment and evaluation remain a challenge and ongoing field of research in many regions (Doran and Parkin, 1994, Brejda *et al*., 2000, Sparling and Schipper, 2004, Liu, 2004; Govaerts *et al*., 2006; Giuffre *et al*., 2006; Lima *et al*., 2008; Cecillon *et al*., 2009; Gartzia- Bengoetxea, 2009). Despite the quantum of soil quality assessment studies conducted so far, a number of methodological issues that have either attracted little or insufficient attentions of scholars are still identifiable. These issues are further discussed below:

First, the majority of soil quality research has been conducted on temperate regions. Similar research efforts on tropical soils are much more limited (Palm *et al*., 1996; Ericksen and McSweeney, 2000; Sanchez *et al*., 2003; Sharma *et al*., 2005; Masto *et al*., 2007). Additionally, compared to nutrient pollution in temperate zones, cultivated tropical soils are likely to develop nutrient deficiencies under continuous cropping without adequate inputs. Smallholder farmers in developing countries are facing

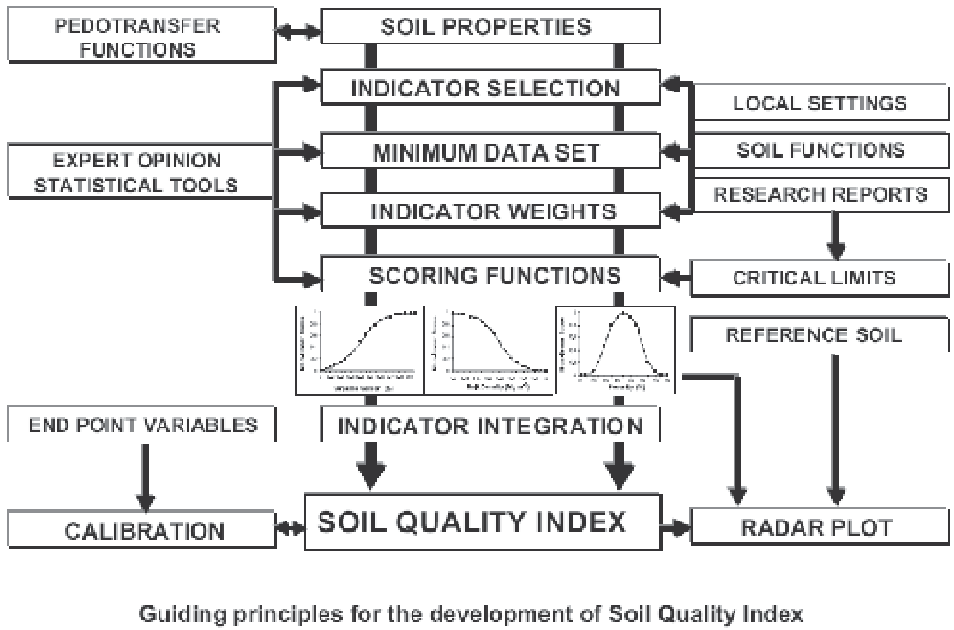


Figure 4. A framework for soil quality assessment adapted from Masto *et al*. (2008)

food insecurity due to environmental degradation arising from severe depletion of nitrogen and phosphorus in many of their soils. Thus, an important challenge for soil quality research in the tropics is to identify quantitative parameters that reflect these nutrient deficiencies (Masto *et al*., 2007). The relative effectiveness of various soil assessment tools and indices need to be examined in the context of cultivated tropical soils.

Second, quantitative assessment of soil quality have been carried out in the past three decades, yet most studies have selectively focused on a limited range of either physical, chemical or biological soil quality attributes (Lal, 1997a,b; 2000; Onweremadu *et al*., 2008). Additionally, few integrated soil quality assessment studies exist but were carried out in well-controlled experimental fields of government institutions or research institutes (Masto *et al*., 2007; Mohanty *et al*., 2007). Till date, long-term comparative studies of soil quality under farmers' field managements are rare. It is therefore recommended that more on-farm research be conducted on farmers' field to determine impacts of existing land use types and management practices on soil quality parameters, as a vital step towards developing a sustainable soil management practices.

Third, there is consensus in the literature that SQ may not be directly measurable, but may be inferred from management induced minimum data sets (MDS) made of chemical, physical and biological properties essentials in term of soil functioning (Acton and Padbury, 1993). However, selection of MDS for soil quality assessment remains a difficult task and a subject of active research and modeling efforts. A cursory review of literature shows that previous studies have largely relied on expert opinion in selection of soil indicators and assigning weight to these indicators. The major shortcoming of this approach is the subjective choice of the soil functions, soil indicators, and the possibility of correlations among them (Lima *et al*., 2008). In contrast to this procedure, multivariate statistical approaches such as Multiple Regression, Principal Component Analysis (PCA) and related Factor Analysis could be used to select few data sets from large data. Though some authors have discussed the potential of these techniques in selection of soil quality indicators (Bredja, 2000a;

Giuffre *et al*., 2006; Lima *et al*., 2008), relatively few examples of their use are found in soil quality assessment studies. Multivariate statistical analyses can provide details on the correlations between parameters often revealing obscured relationships between parameters to potentially give new insights into the processes controlling the variability in the dataset. For instance, principal component analysis (PCA) has routinely been applied in a wide variety of fields in the natural and social sciences. Its primary function is to explore complex data sets of many dimensions, collapsing many variables, based on their correlations, to a few factors that explain the observed variability and thereby reveal underlying data structure and highlight relationships between the variables. Although the analysis does not provide a mechanism or demonstrate causality, it does provide a quantitative measure of relatedness of variables to one another that can be suggestive of the underlying processes controlling the variability in the dataset.

Fourth, conceptual and practical evaluations of soil quality indicators are mostly limited to the top soil properties or plough layer. Argueably, this research focus is limited and does not allow for full understanding of the very wide differences between various soils and cropping systems. If we are to focus on sustainable agriculture, environmental problems and feeding the increasing population, there will have to be a long-term soil management that requires integrated research on the root zone limitations including both topsoil and subsoil (Rengasamy, 2000). It is important to note that topsoil and subsoil are deeply involved in interactions with the plant and the environment. Thus, soil quality is also affected by subsoil constraints such as sodicity, compaction, salinity, acidity, nutrient deficiencies, presence of toxic elements (chemical) and low microbial activity (biological). The key towards realizing potential crop yields would be to gain better understanding of subsoils and their limitations, then develop options to manage them practically and economically. Therefore, there is a need for more robust soil quality assessment tools and analytical approaches that will incorporate both topsoil and subsoil constraints, particularly under dryland/irrigated cropping systems.

Fifth, an important consideration is the spatial scale for assessing soil quality. Previous studies have concentrated largely on the field, plot or farm level scale. When considering the impact of land use and management practices on soil quality, of particular importance for future work is understanding how we can scale up and extrapolate from plot and farm scale research to emerging patterns appearing at the scale of an entire basin and watershed. With the increased promotion of a watershed approach to natural resource management, the need for analytical tools that can deal with spatial and temporal heterogeneity and the multi-scale nature of complex soil quality issues can be quite valuable.

Sixth, the chemical analysis of soil quality indicators involve time, money and energy. So use of sensors (e.g. hyperspectral remote sensing) and portable soil test kits should be developed and promoted for more frequent monitoring of soil quality.

Last, most of the previous studies on soil quality assessment and indicator selection have been conducted by soil scientists and agronomists. In consequence, the issue of spatial variability in soil quality indicators has been less evaluated. There is a dire need for wide application of spatial methods in soil quality research. With recent development in spatial method of GIS, soil quality research stands to benefit particularly, in the present concern for precision agriculture.

SOIL HEALTH CARD

Swasth Dhara, Khet Haraa

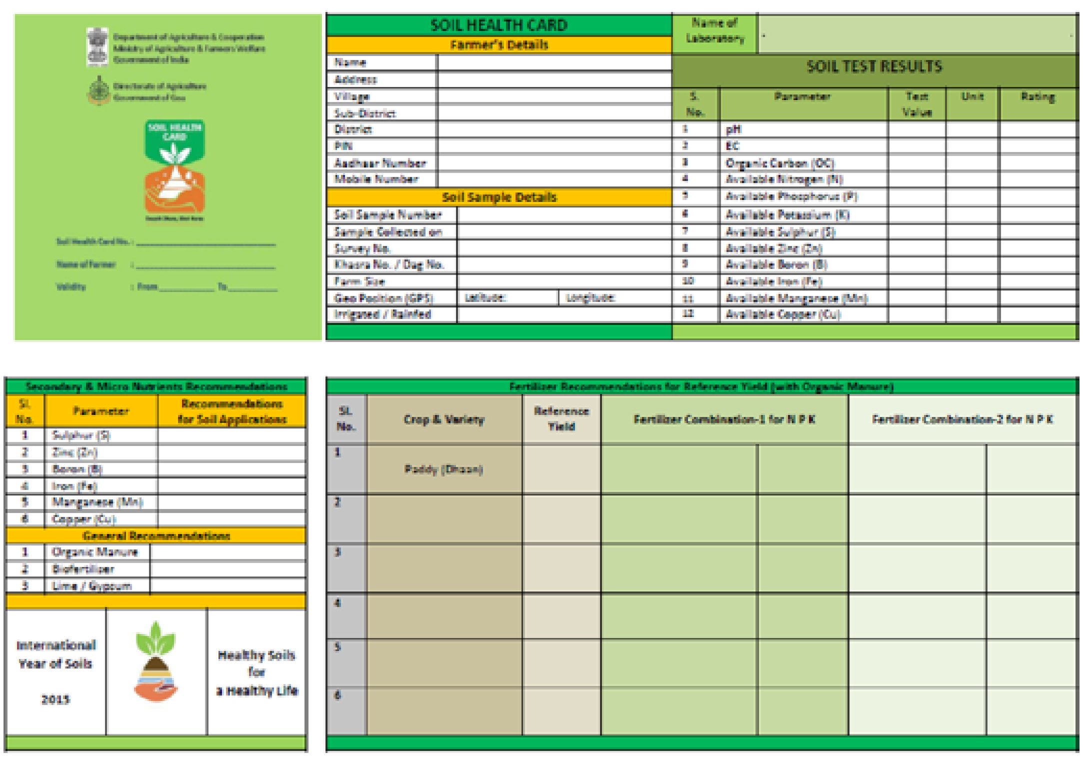
5. Government of India initiatives on Soil Health Assessment

Soil Health Card Scheme is a scheme launched by the Govt of India in February 2015. Under the scheme, the government plans to issue soil cards to farmers which will carry crop-wise recommendations of nutrients and fertilizers required for the individual farms to help farmers to improve productivity through judicious use of inputs. All soil samples are to be tested in various soil testing labs across the country. Thereafter the experts will analyze the strength and weaknesses (micro-nutrients deficiency) of the soil and suggest measures to deal with it. The result and suggestion will be displayed in the cards. The government plans to issue the cards to 14 crore farmers. An amount of ₹ 568 crore (US$84 million) was allocated by the government for the scheme. As of July 2015, only 34 lakh Soil Health Cards (SHC) were issued to farmers as against a target of 84 lakh for the year 2015-16.

Objectives of Soil Health card scheme are as follows:

- To issue SHCs every 3 years to all farmers of the country.
- To strengthen functioning of Soil Testing Laboratories (STLs) through capacity building, involvement of agriculture students and effective linkage with Indian Council of Agricultural Research (ICAR)/State Agricultural Universities (SAUs).
- To diagnose soil fertility with standardized uniform procedures for sampling and analysis across the states.
- To develop and promote soil test-based nutrient management by designing fertilizer recommendation in targeted districts.
- To build capacities of district and state level staff and of progressive farmers for promotion of balanced and integrated nutrient management.

The format of the Soil Health Card is given below:



SOIL HEALTH CARD			
Farmer's Details			
Name			
Address			
Village			
Sub-District			
District			
PIN			
Aadhaar Number			
Mobile Number			
Soil Sample Details			
Soil Sample Number			
Sample Collected on			
Survey No.			
Khasra No. / Dag No.			
Farm Size			
Geo Position (GPS)	Latitude:	Longitude:	
Irrigated / Rainfed			

Name of Laboratory				
SOIL TEST RESULTS				
S. No.	Parameter	Test Value	Unit	Rating
1	pH			
2	EC			
3	Organic Carbon (OC)			
4	Available Nitrogen (N)			
5	Available Phosphorus (P)			
6	Available Potassium (K)			
7	Available Sulphur (S)			
8	Available Zinc (Zn)			
9	Available Boron (B)			
10	Available Iron (Fe)			
11	Available Manganese (Mn)			
12	Available Copper (Cu)			

Secondary & Micro Nutrients Recommendations		
Sl. No.	Parameter	Recommendations for Soil Applications
1	Sulphur (S)	
2	Zinc (Zn)	
3	Boron (B)	
4	Iron (Fe)	
5	Manganese (Mn)	
6	Copper (Cu)	
General Recommendations		
1	Organic Manure	
2	Biofertilizer	
3	Lime / Gypsum	
International Year of Soils 2015		Healthy Soils for a Healthy Life

Fertilizer Recommendations for Reference Yield (with Organic Manure)						
Sl. No.	Crop & Variety	Reference Yield	Fertilizer Combination-1 for N P K		Fertilizer Combination-2 for N P K	
1	Paddy (Dhaan)					
2						
3						
4						
5						
6						

Management strategies to Improve soil health/quality

Based on the findings of various studies, the following research, developmental and policy strategies are suggested for effective soil quality improvement, management and assessment (Sharma *et al*., 2015).

- **Erosion control through effective soil and water conservation (SWC) measures**: In order to protect the fertile top soil, it is of prime importance that there should be no migration of soil and water out of a given field. This can be achieved, if the existing technology on soil and water conservation (SWC) is appropriately applied on an extensive scale. The cost for *in situ* and *ex situ* practices of SWC has been the biggest concern in the past. There is a need to launch 'Land and Soil Resource Awareness Programme' (LSRAP) at the national level to educate the farming community using all possible communication methods. These aspects are discussed in a companion Chapter.
- **Revamping and reorientation of soil testing programme in the country:** About more than 700 Soil testing laboratories situated in the country need to be revamped, restructured and given fresh mandate of assessing the soil quality in its totality, including chemical, physical, biological soil quality indicators and water quality. The testing needs to be on intensive scale and recommendations are required to be made on individual farm history basis. Special focus is required on site specific nutrient management (SSNM). Soil Health Card (SHC) needs to updated periodically. Soil health cards should also include some sensitive physical and biological parameters along with chemical parameters. Soil quality maps of intensive scale need to be prepared. District soil testing laboratories need to be renamed as 'District Soil Care Laboratories' and required to be well equipped along with qualified manpower for assessing soil quality indicators including micronutrients. Fertilizer application need to be ascertained based on soil tests and nutrient removal pattern of the cropping system in a site- specific manner. This will help in improving soil health by correcting the deficiency of limiting nutrients. The private sector can also be encouraged to take up the Soil Care Programs with reasonable costs using an analogy of 'Soil Clinics for Diagnosis and Recommendation' (SCDR).
- **Encouraging agricultural management practices that enhance soil organic matter**: Soil management practices such as use of organic manures (composts, FYM, vermi-compost), legume crop-based green manuring, tree-leaf based green manuring, crop residue recycling, sheep-goat penning, organic farming, conservation tillage, inclusion of legumes in crop rotation need to be encouraged for enhancing organic matter in our soils in the semi-arid tropics and tropics (Sharma *et al*., 2002, 2004). Similar to inorganic fertilizer, provision for incentives for organic manures including green manuring can also be made so that growers may be motivated to take up these practices as in-built components of integrated nutrient management (INM) system. Pronounce a policy to attain at least 0.04% per annum growth in soil organic matter content by banning destruction and encouraging use of organic manures of diverse shades on one hand and employing organic matter conservation management on the other.
- **Promotion of other bio-resources for enhancing microbial diversity and ensuring their easy supply**: There is a huge potential to develop and promote bio-fertilizers and bio-pesticides in large scale to facilitate enhancement of soil fertility and soil biological health. Use of toxic plant protection chemical also needs to be reduced. In addition to this, there is a need to focus on advanced research for enhancing microbial diversity by identifying suitable gene pools.
- **Adoption of precision farming for enhanced input use efficiency:** The present level of use efficiency of fertilizer nutrients, chemicals, water and other inputs is not very satisfactory. More

focus is required to improve input-use efficiency. The components required to be focused could be suitable machinery and other precision tools for placement of fertilizers, seeds and other chemicals in appropriate soil moisture zone so that losses could be minimized and efficiency could be increased. This aspect has a great scope in rainfed agriculture. This will also help in increasing the water use efficiency (WUE).

- **Amendment of problematic soils:** The soils need to be protected from degradation due to soil physical constraints, salinization, alkalinity, erosion, etc. The soil amendment programmes should be national programmes linked with the 'state agricultural departments'.
- **Maximization of land cover:** Covering the land with cover crops such as legumes, natural and pasture grasses, mulches with separable crop residues will help in protecting the land from the direct beatings of high energy rainstorms, ill effects of extreme temperatures during summer and winter, reduction in evaporation, enhanced biological activity due to congenial soil habitat conditions, higher C sequestration, etc. Hence, this concept needs to be propagated extensively among the farming community to help improve soil quality.
- **Conservation agriculture with minimum tillage and spreading of crop residues as mulch needs to be promoted**: It helps in protection of soil structure, moisture conservation, enrichment of chemical and biological soil health, enhances soil organic carbon sequestration and encourage more entry of rain water in to the soil profile and minimize soil erosion. Specialized equipments and knowhow for conservation agriculture should be made available to the farmers. Legislation should be enacted to stop burning of crop residues by the farmers. Some incentive to the farmers may be given to adopt conservation agriculture rather than burning of crop residues.
- **Revamping of land care programs and associated functional bodies:** Organized functional statutory bodies at the Centre and in the States on Land Care and Soil Resource Health are necessary to effectively coordinate the Land Care and Soil Health Restoration and maintenance programmes. Some of the activities of land care can be linked with the National Rural Employment Guarantee Programme. Awareness among the farmers may be developed about the importance of maintaining soil health for sustainable agriculture.
- **Research focus is needed for developing critical levels of some of the soil quality indicators** for which the information is not available for the Indian conditions. Case studies should be planned keeping in view three aspects, viz. soil quality restoration, improvement and maintenance. Systematic research is needed to study soil resilience for diversity of edaphic, climatic and management conditions. It would be relevant to study soil quality, resilience and sustainability quantitatively under long-term restorative management practices in different crop growing environments.
- **Research focus is needed for the use of modern tools and techniques for rapid estimation of soil quality.** The chemical analysis of soil quality indicators involve time, money and energy. So use of sensors (e.g. hyperspectral remote sensing) and portable soil test kits should be developed and promoted for more frequent monitoring of soil quality.

5. Conclusion

For providing holistic information on soil health, apart from chemical properties, determination of key physical and biological properties of soil should be made mandatory in soil testing laboratories and should be included in soil health cards. The multivariate statistical method, PCA, was very effective in selecting the MDS from a larger existing data set. This approach has the potential to integrate biological, chemical, and physical data for ecological management applications where such integration is often lacking. With regard for both productivity and sustainability, applying residues could maintain soil quality for a longer period than if they were removed for other uses or burnt. Site specific technologies viz., optimum tillage practices and mulching, use of suitable cropping system, amendment of acid soils and salt affected soils and amelioration of soil physical constraints, efficient use of organic manures and fertilizers, which can improve the soil health. Resource conservation technologies like conservation agriculture may be promoted for improving resource use efficiency and improving soil health. Regular precise and rapid monitoring of Soil quality index would help in providing advice to the growers/farmers to choose suitable management practices and to improve these dynamic indicators for enhancing soil quality to achieve desired functional goal of sustainable intensification of agricultural production.

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Digital Farming - A Revolution in Indian Agriculture for Optimizing Resources

Vinod Kumar Singh

ICAR-Central Research Institute for Dryland Agriculture, Hyderabad

Agriculture is a deep-rooted culture in Indians. Scientific and technological advancements in agricultural research made the country from famine to adequacy and low to surplus production. Diverse agricultural systems, varied land holding sizes, traditional knowledge of the farmers and scientific research innovations allowing the Indian agricultural system to be resilient from aberrations. Now India agriculture is moving nutritional security of the citizens by producing high quality and nutritional produces. Government is encouraging to go for high input use efficient cropping systems, high nutritional crops, doubling farmers' income and natural farming. Which enables us to achieve optimized resources use, enhanced soil quality, reduced wastage of inputs and increased farm income. In this context imparting training to the farmers on technological advancements in farming is a continuous process, but is limited due to insufficient number of extension personnel in the country. It is also understood from the fact that farmers are not using resources at full potential. The knowledge gap is evident among the farming communities. Judicious use of resource is possible when farm operations are automated and resource requirements are given to the farmer in the form of meaningful and understandable alerts.

Digital Farming

Digital farming is a process of automating the farm activities, which is a subset of Digital agriculture under the information and communication technologies (ICT). It is a kind of precision agriculture with data driven methods and devices for managing and optimizing the production systems. In the recent past, the applications of information technology applied in the form of ICTs, also known as e-agriculture, focuses on the enhancement of agricultural and rural development. E-agriculture is one of the action lines identified in the declaration of the World Summit on the Information Society (WSIS), published in 2005. ICT comprise networks, mobiles, devices, services, and applications that aid the processing, management, and exchange of data, information, or knowledge with farming communities. It includes a broad range of converging technologies, including traditional telecommunications, television and video, radio, CD-ROMs, cell phones and smart devices, and several modern technologies such as computers and the Internet, sensors, geographic information systems (GIS), satellites, and etc. The roll of ICT is to transfer information from one point to another. It has certainly revolutionized agriculture sector, but its utility was restricted to disseminating agricultural scientific research innovation and recommendation to the stakeholders, passive decision support systems, market linkages and payment gateways. ICT has helped to address several challenges associated with the traditional agriculture at farmer level, but not at farm or plant level. Now agriculture sector is looking for quality produces, safety of the farmer and optimum utilization of farming resources. At this juncture this sector needs fully automation in farm operation for monitoring at farm/plant level. Therefore, the farmer will know timely requirements of the field/plant, its precise location and exact quantity for application. Digital farming is a way to optimize the resources. The implementation of digital farming can be divided into three categories. The first category is installing/deploying sensor networks, Internet of Things (IoT) devices, drones, cameras and wireless communication devices in the field for real time field data collection. Second one is applying artificial intelligence (AI) / machine learning (ML) algorithms for data analytics and provide recommendations to alert farmers. Third category is using automated farm machineries like robots/drones for field operations. The increase in adoption of digital technologies like drones and AI in agriculture has been evident with Government of India support. This concept will bring impactful changes in sustainable/precision agriculture in coming years.

1. Real time field data collection and management

Agricultural field operations are sequence of many activities from soil preparation to harvesting namely finding initial soil status, timely irrigation, sowing, micro climate status, nutrient management, biotic stress management and harvesting. Data-gathering becoming a key to success in digital farming operations as most farms are situated in remote areas where regular farm monitoring and management becomes difficult. Collecting real time field data in regular time intervals helps to understand critical requirements, which leads to timely action. Drones with multispectral cameras are used to take field shots to get insights of crop health. Various IoT and weather sensors located across the field collect various micro climatic conditions from the environment like lighting, humidity, temperature, and soil condition. Gathered the appropriate weather data allows farmers to see how different weather patterns may affect their water and soil. The integration of IoT sensors, and electronic communication systems collect a large amount of data with high accuracy. Ground-based and plant sensors are used to collect information about the soil and water. For soil, these sensors measure texture, organic matter, salinity levels, and nutrient status. Therefore, it requires data managers, storage systems and automatic data backup facility. Cloud-based services are useful for real-time data storage with Internet connection that offers more flexible resources than the conventional server-based solution. The received data from these devices are aggregated onto data platforms indifferent categorical subjects where it can be processed and analyzed to help farmers make better decisions on how to precisely optimize their farm resources.

2. Data analytics and recommendations

Farming rely upon learning by doing, rather than explicit knowledge transfer. This creates real challenges, such as how to avoid human error, misunderstandings and cognitive bias. Data analytics is the process of examining and discover hidden patterns, unknown correlations and other useful information that can be used to make better decisions and meaningful insights for farming. The field data collected, mainly from different sensors and drones has to under go deep analysis to take precise actions in time. AI and ML has become a preferred approach due to increased computational power, storage capacities, and availability of large datasets. Field data tracking helps farmers better manage their operations and creates real insights into pest protection, fertilizer and herbicide application, irrigation and harvest timing. With the availability of a wide range of data and more information, they can make decisions that are tailored to the specific needs of their farms. That results in higher productivity and profitability, optimized fertilizer use and lower input costs. Data visualization also helps farmers to identify the state of vegetation and problem areas in agricultural fields. Crop health monitoring, mostly based on normalized difference vegetation index (NDVI) is a method that is used to determine the health of crops through the analysis of drone and satellite imagery. AI based deep learning algorithms allows to assess the health of crops and detect crop variability. Data analysis of collected information also provides forecasting of harvesting stage. It allows farmers to make better decisions on when to harvest, plan next season crops and its fertilization, analyze field variability, and many other things. After analysis, recommendations should be given in the form of alerts or actionable format, which can be communicated, to a device to take action. For example, identified weed information communicated to control unit for an action such as plucking of weeds or spray of some herbicide.

3. Use of robots/drones for field operation

Agricultural machinery is a device that significantly reduces the amount of human labour required for farming. Autonomous farm machineries like robots and drones perform numerous farm activities precisely to optimize the farm resources, which are more suited for the present day contest. They are critical equipment for performing repetitive tasks faster, cheaper, and more accurately. Agricultural field operations were classified as seeding, transplanting, weeding, crop scouting, stress detection, spraying and harvesting for the development of autonomous farm machinery.

Precision planting is an automated approach to optimizing the planting of seeds. Autonomous seeder and planter is a versatile machine specialized for seeding and planting. It allows for better seed spacing, better depth control, and better root systems. Robot tractors is a self-driving vehicle for carrying agricultural sowing tools with GPS guidance systems for auto steering and high navigation. Weeds controlling is an important task and difficult to strip away. Chemical solution is not the solution. Therefore, weed-management robots have an advanced AI models to distinguish weeds and destroy or burn with laser beam. Drone deploys plant health tools to have an autonomous scout for identifying stress areas that needs pesticide, assess drip irrigation leaks and help to determine the exact time of crop ripe and harvest stage. This process involves attaching multispectral and hyper-spectral cameras, satellite imagery, and AI applications on tractors/drones. By using drones farmers can get highly accurate aerial insights, quickly assess crop health, make better decisions, increase productivity and ultimately lower costs. These technologies facilitate variable rate applications (VRA) focuses on the automated precision application of materials like herbicides and chemicals. Eventually, aerial and ground robotics will work in tandem to capture data, analyze it using AI, and then act on it. Therefore, it provides advantages, as improved fresh produce quality, lower production costs, as well as the ability to work autonomously to supplement or replace human labour. Harvesting is one of the most common area where robots are used in agriculture today. Agricultural robots pick up apples, gather strawberries and harvest lettuce. They use advanced machine vision to detect harvesting stage of crop to be picked and transferred.

Conclusion

Digital farming can bring more precision management options in Indian agriculture, which makes farming more brighter and cost effective. This concept offers substantial value to the farmers in their efforts from field monitoring to variable rate application. It offers an end-to-end solution to optimize production, precisely manage their operations, and increase farm income. Potential benefits are judicious use of inputs (chemicals, fertilizers, water, fuel etc.) improved quality of produce, higher yield, reducing environmental footprints and risks mitigation. This also brings new business avenues like data analytics, data storage, drones management, robot development, designing wearable devices, software application and many more. It encourages/attract educated youth into agriculture as innovators and provided job opportunities.

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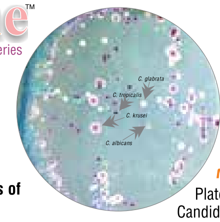

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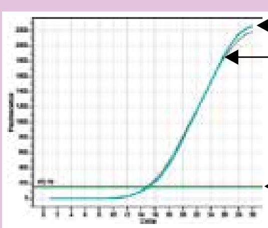
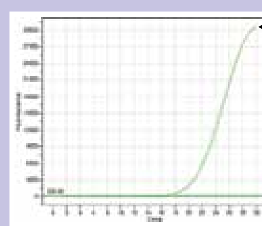
Sample	Ct value
Positive control	14.89
Salmonella spiked in milk	15.32
Negative control	N/A



Detection limit in Milk : upto 1 cell (pre-enrichment)

Sample	Ct value
Pork	16.56
Negative control	N/A



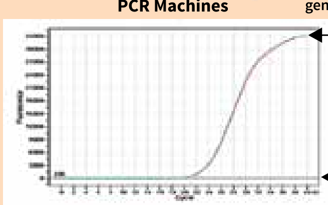
(Sensitivity : 0.01%)

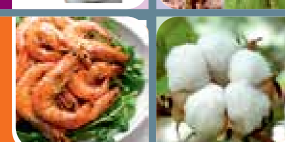
Food Pathogen Detection Kits

Meat Adulteration Detection Kits

PCR Machines

Sample	Ct value
WSSV gene	19.49
Negative control	N/A

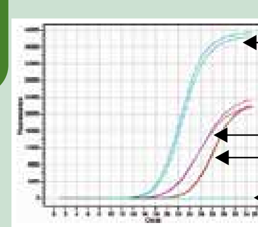




WSSV Detection Kits

GMO Detection Kits

Gene	Ct Value
35S	15.43
NOS	20.19
rbcL	13.9
Negative Control	N/A



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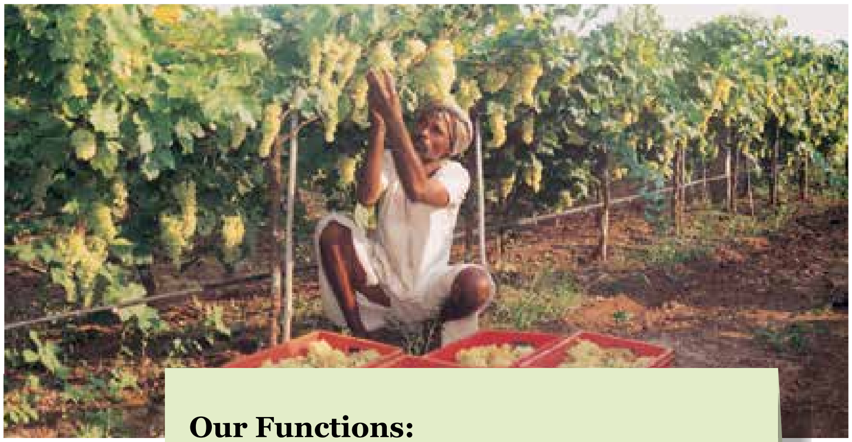

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