

AGRIFRONTLINE

The Voice of Agriculture

Digital Agriculture and Climate Forecasting: How Technology is Supporting Climate Change Adaptation

Sumesh Sharma¹, Isha², Himshikha², Kamlesh Haritwal¹

1. Introduction

Among the many sectors highly sensitive to climate variability, agriculture is one of them. Due to increasing carbon dioxide concentrations, rising temperatures, and fluctuating rainfall patterns, climate change has already had an impact on agricultural production systems throughout the world. At the same time, agricultural practices also emit substantial GHGs, particularly from crops and livestock. Furthermore, digital agriculture

has been defined as employing the latest technologies for enhanced precision agriculture, such as UAVs, IoT-based devices, robotics, satellites, and data analysis, for efficient real-time and/or online management. Figure 1 depicts PA's core workflow, including building blocks for Digital Farming. PA utilises raw data from various sources, including satellite, remote sensing, and mobile sensing, to identify deficiencies and improve crop production. These tools allow the farmer

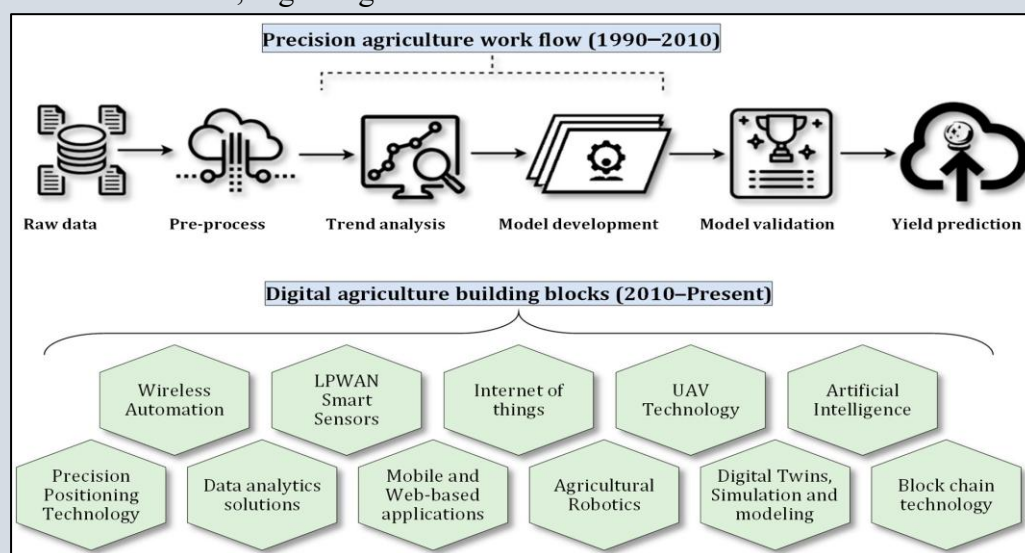


Figure 1. A comparison between the building blocks of precision agriculture and digital agriculture

¹ Research Scholar, Department of Agriculture Extension and Communication, College of Agriculture, Swami Keshwanand Rajasthan Agricultural University, Bikaner, Rajasthan

²Research Scholar, Department of Extension Education, College of Agriculture, Punjab Agricultural University, Punjab

to closely monitor soil conditions, water levels, and changes in weather patterns, enabling greater production at lower operating costs (Basso *et al.*, 2020; Sparrow *et al.*, 2021). For instance, satellite communications can help assess crop water status and quality using high-definition UAVs. In relation to the use of automation in agricultural activities, wireless sensors play an important role in implementing smart irrigation methods and assessing water usage, enabling real-time monitoring of nutrient levels in agricultural settings.

2. Concept of Digital Agriculture

Digital agriculture refers to the use of digital technology to aggregate, analyse, and leverage agricultural data to improve agricultural productivity, sustainability, and resilience. Rather than replacing farmers' knowledge, digital agriculture aims to supplement decision-making by combining traditional knowledge with real-time data and scientific predictions. Technologies such as satellite, sensor, mobile, artificial intelligence, and cloud computing form the backbone of digital agriculture (Klerkx *et al.*, 2019). What makes digital agriculture different from previous mechanisation initiatives is its predictive nature. Data is obtained from various sources, such as soil, weather, crops, and markets, and then combined to

provide management information. This method is extremely useful for adapting to climate change because it enables adaptation to occur in line with climatic changes.

Impact of Climate Change on Agriculture

Climate change patterns are one of the global issues that have been affecting the present and future environmental conditions. Climate change is mostly linked to an increase in CO₂ concentration above 400 ppm in the environment, thus producing causing increase in temperature, rainfall, drought, and weather extremes such as floods, frost, etc (Patterson *et al.*, 2013). Climate change patterns are one of the global issues that have been affecting the present and future environmental conditions.

• Impact on Crop Production

Rapid growth in population also leads to an increase in the demand for food production on a global scale. Thus, increased crop productivity per unit of land area becomes essential. However, many crops have not yet attained their full potential in many agricultural areas due to inadequate climatic conditions as well as inefficient agricultural practices. Among the climatic factors that influence crops include increased levels of temperatures, increased levels of carbon dioxide concentration in

the atmosphere, as well as irregular levels of rainfall. Climate change is also influencing the timing as well as the duration of planting as well as harvesting. Climate change also influences droughts, floods, pests, diseases, as well as a reduction in crop yield. Thus, crop yield is being reduced, as is the income generated. Based on the available data, crop yield is increasing at a slower rate than the human population. Thus, there is an increase in the potential risks of food insecurity. Based on projections, major crops such as maize, wheat, and rice are expected to face severe yield reduction as well as severe increased food price levels in the coming years.

• Impact on Soil

To provide nutrients for plant growth and supporting activities in agriculture, healthy soils plays a very important role. Despite there being various aspects that affect the development or formation of soils, climate remains the most pivotal factor in determining soils' structures or compositions in relation to fertility and their capacity or ability to resist erosion processes (Karmakar *et al.*, 2016). Climate change phenomena, including circumstances brought about by increased temperatures, heavy rainfall events, droughts, or storms, have exposed soils to various risks in relation to their deterioration or degradability in the near

future (Lal *et al.*, 2011). The elevated level of CO₂ gases in addition to increased temperatures and rain intensity have important implications for soils' fertility or their functions in plant growth or in agriculture at large. The elevated level of CO₂ gases causes acid soils with a tendency to reduce pH levels in soils with undesirable implications for plant growth or development in addition to reducing biodiversity while increasing temperatures lead to increased rates of nutrient cycling processes with undesirable consequences in relation to reduced moisture levels in soils with an increased potential for erosion or degradation in the near future.

Increasing Precipitation

- increases soil moisture or wetness
- Increases surface runoff and erosion
- Nutrient loss through leaching
- Increases reduction of iron and nitrates
- Increases volatilization loss of nitrogen
- Increases productivity in arid regions

Reduces Precipitation

- Reduces soil organic matter
- Soil salinization
- Reduces nutrient availability

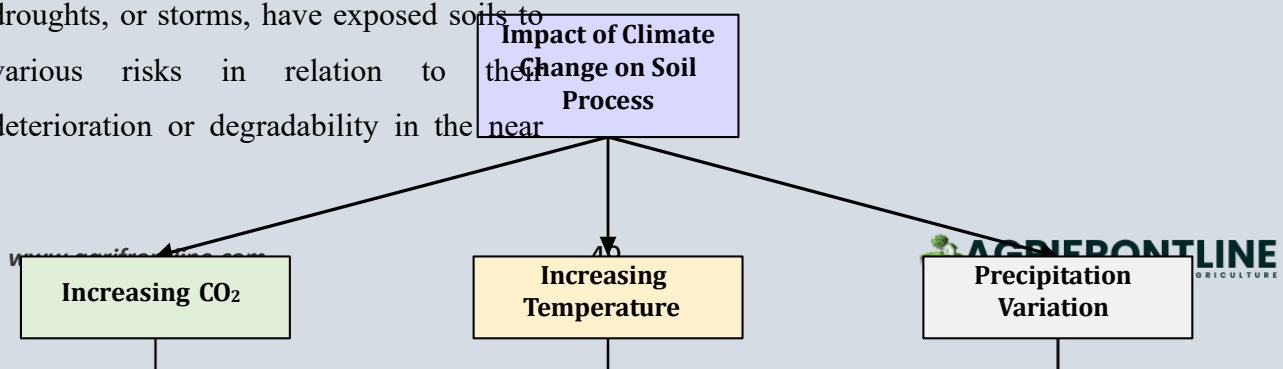


Figure 2. The possible influence of climate change on soil activities

- **Building Climate Resilience through Precision and Digital Agriculture**

Climate change poses a serious threat to agricultural productivity and global food security, making climate resilience a priority for modern farming systems. One effective way to strengthen resilience is by reducing greenhouse gas emissions while using water, nutrients, and land more efficiently. Precision and digital agriculture offer practical tools to achieve this balance by helping farmers produce more with fewer inputs. Since agriculture is a major source of methane and nitrous oxide emissions, largely due to inefficient irrigation and fertiliser use, improving nutrient and water management plays a critical role in lowering agriculture's climate footprint (Vallero, 2019; Hassan *et al.*, 2022). Precision nutrient management

focuses on matching fertilizer application with crop demand and soil conditions, which improves nutrient use efficiency and reduces excess nitrogen losses. For example, tools like crop or soil sensors, decision support systems, remote sensing technologies, and variable-rate technologies allow for accurate application of nutrients at appropriate times and places. These methods do not only minimize nitrous oxide emission but can also minimize costs and maximize crop yields. Moreover, precision water management can help farmers cope with effects of climatic changes by optimizing water usage depending on real-time measurements of water held in the soils by crops (Chivenge *et al.*, 2022). In addition to improving water use efficiency, precision water management can protect groundwater resources against contamination by nitrates resulting from agricultural activities. In water stress-prone areas with low rainfed crop yields, precision water management can allow for optimized water usage depending on real-time measurements of water held in the soils by crops.

3. Digital Agriculture Adoption and Climate-Smart Agriculture

Digital agriculture has a great potential to enhance farm productivity and reduce poverty and hunger, and it is also a contributor to climate change because farm production becomes intensive, evidence-based, and ecologically conscious. It assists farmers in making better decisions using advanced sensors reduce environmental degradation. However, this would depend mainly on the rural infrastructure, availability and accessibility of technology, training of farmers, and institutional support, especially for small-scale farmers. Various research works carried out across different regions make it clear that although the benefits of digitalization in agriculture attract the farming community, the extent of digitalization still depends on the capacity of the economy, the culture of farming, and the complexity of digitalization itself. Although the simple trend of digitalization can be observed, the complexity of digitalization still has low adaptation rates for farm practices to be effective in the long run against climate change like drought, flood, heat, and pests. In order to cope with the consequences of climate change in the near future, precision and climate-smart farming RS satellites, and mobile phones linked with AI and automation that reduce inputs in farming a practices have come to

the forefront to mitigate the likely risks associated with climate change risk factors like drought, flood, high temperatures, and pests for the farming community worldwide. Climate-smart agriculture (CSA) addresses issues related to productivity, climate change, and reduction of greenhouse gas emissions by developing an optimal framework for the management of crop, animal, land, water, and energy resources with the greatest possible efficiency. The digitalization of farming is largely associated with climate-smart practices by promoting precision irrigation, crop modeling, greenhouse application, and knowledge sharing among the farming community, research scientists, and the government.

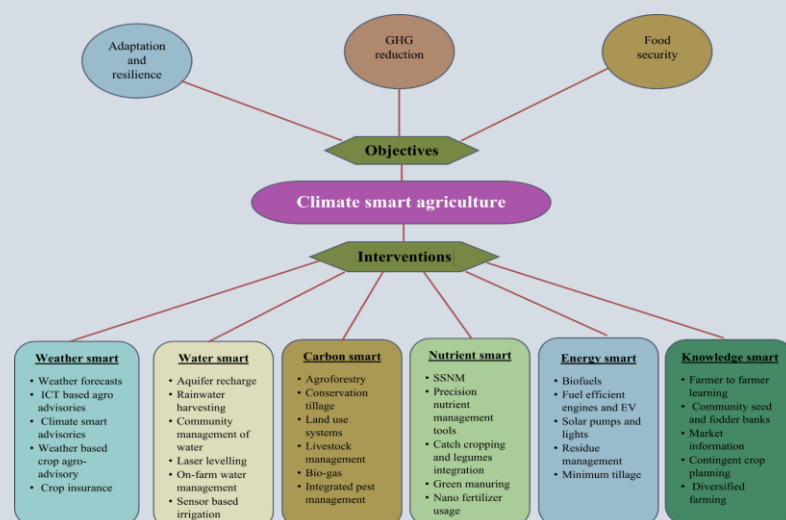


Figure 3. The framework of climate-smart agriculture objectives and interventions for different environments.

4. Technology-Driven Approaches to Climate-Adaptive Farming

Climate change adaptation in the agricultural sector is not the elimination of climatic crisis, but rather the anticipation, absorption, and adaptation to climatic shocks to sustain productivity. In such adaptation, digital technologies assist by translating climatic risks into action, being extremely beneficial since it turns climatic risks into decisions. In essence, digital technologies assist in adaptation to climatic risks in the agricultural sector by facilitating actionable adaptation in the following ways:

5. Anticipatory Decision-Making through Climate Forecasting

One of the most important contributions of digital technology to adaptive action to climate change is its ability to promote an anticipatory approach to farm decisions,

rather than the sometimes-reactive decisions in traditional agriculture. With the availability of information generated by forecasts of climatic changes and satellite images, it is now possible for individuals in agriculture to decide where, when, and what to expect in the next season of precipitation or temperature increases (Hansen *et al.*, 2011). For instance, in areas that have in recent past seen delays in the onset of the monsoon season, information delivered by digital forecast system helps in adjusting the timing for harvesting or in choosing the crop species with short growth cycles or that which has innate drought-resistant traits. The use of information in adapting to the impacts of climate change effectively helps in reducing the risk of crop loss and may be described as one method with major role in promoting the adaptation process (IPCC, 2022).

6. Reduction of Climate-Related Risk and Losses

Extreme weather events such as heatwaves, floods, or droughts often tend to rise in frequency and intensity. Digital early warning systems utilize the current weather conditions, satellite images, and models to alert the farmer of any impending danger using the weather data that is collected in real-time. This serves as an early warning to the farmer to act accordingly, such as harvesting the crops early, irrigating them temporarily, or even relocating the farm animals to a safe place. The available empirical evidence suggests that the application of EWS can help in reducing the losses, especially with regard to yield, as a result of the economic damage that is reduced by responding to the extremes of nature in a timely manner (FAO, 2019). In this regard, it is worth noting that technology assists in enhancing the coping capacity, which can be described as one dimension or aspect of adaptation in relation to the changes in climate

8. Efficient Resource Use under Climate Stress

The changing climate poses an increased burden on the already stressed important sectors related to agriculture, such as water reserves. Digital technologies such

as IoT sensors and an automated irrigation system provide tools that take into account weather changes in decision-making processes. Farmers align irrigation and fertilization with actual crop demand and forecasted weather conditions to reduce resource use without impacting yields (Wolfert *et al.*, 2017). For example, in low rainfall, sensor-based irrigation scheduling enables farmers to use water preferentially during critical crop growth stages. Such efficiency decreases vulnerability to short water supply and heightens adaptive capacity in water-stressed conditions.

9. Localized and Context-Specific Adaptation Strategies

Another major problem of traditional advisories is that they are generalized in nature, which can be avoided by adopting digital agriculture tools that use farm data coupled with climate predictions to provide advisories at a micro-level, where AI models can use local climate patterns, soil conditions, and response of crops to provide advisories that can be implemented by the farmer. The localization is a critical element for adaptation to the climatic change because of the consideration that climatic change can occur in a different manner on a small geographical scale. Digital decision support systems are designed to

adaptation strategies based on the local conditions rather than regional averages (Liakos *et al.*, 2018).

10. Strengthening Adaptive Capacity of Smallholder Farmers

Due to lack of sufficient information, small scale farmers in developing countries often face challenges to adapt to the climate change. In mitigating those challenges, mobile technologies play a crucial role. Since climate advisories can be easily disseminated through a farmer's phone, research shows that when farmers are given information about climate change through various digital platforms, they are likely to adopt adaptive practices such as changing plant timing or even changing the variety of irrigated plants (Aker, 2011).

11. Supporting Long-Term Climate Adaptation Planning

Other than the effects that are immediate, digital technology significantly contributes to long-term adaptation by providing data applicable in the planning. Using information from long-term climate projections and other data from yield history and soils helps in determining vulnerable areas and areas with good potential for shifting or the future use. These digital analyses and findings inform

various decision-making bodies and policymakers enable them to plan and formulate policies and agriculture development plans geared towards adapting and fighting the effects of changing climate concurrently.

12. Conclusion

Digital agriculture and climate forecasting can be considered important tools in finding a solution in relation to the increasing problems of climate change. Since digital agriculture can help in the decision-making process, considering this as an effective tool in helping agriculture cope with an ever-changing climate. It can contribute significantly in finding a solution to produce more food in relation to the increasing needs of the world's population, providing a better quality of products. Therefore, considering this in a positive aspect, the challenge of the future is providing a more agricultural food supply, eliminating pollution in the natural world, increasing agricultural produce, providing fair food distribution, and fighting against malnutrition, which ultimately aims for food security in the world. There is a willingness to make change, along with the presence of the modern technologies. Digital agriculture does not only offers new technologies, but it also uses these technologies to provide a better and more accurate farm

management system and information fusion. Besides increased profitability, due to better management practices and the development of information systems in agriculture, digital agriculture provides many benefits, including increased

product quality, improved sustainability and lower risk in the management system, food safety using product traceability, environment protection, and rural development.

References

1. Aker, J. C. (2011). Dial “A” for agriculture: A review of information and communication technologies for agricultural extension in developing countries. *Agricultural Economics*, 42(6), 631–647.
2. Basso, B., & Antle, J. (2020). Digital agriculture to design sustainable agricultural systems. *Nature Sustainability*, 3(4), 254–256.
3. Chivenge, P., Zingore, S., Ezui, K. S., Njoroge, S., Bunquin, M. A., Dobermann, A., & Saito, K. (2022). Progress in research on site-specific nutrient management for smallholder farmers in sub-Saharan Africa. *Field Crops Research*, 281, 108503.
4. FAO. (2019). *Digital technologies in agriculture and rural areas: Briefing paper*. Food and Agriculture Organization of the United Nations.
5. Hansen, J. W., Mason, S. J., Sun, L., & Tall, A. (2011). Review of seasonal climate forecasting for agriculture in sub-Saharan Africa. *Experimental Agriculture*, 47(2), 205–240.
6. Hassan, M. U., Aamer, M., Mahmood, A., Awan, M. I., Barbanti, L., Seleiman, M. F., Bakhsh, G., Alkharabsheh, H. M., Babur, E., Shao, J., *et al.*, (2022). Management strategies to mitigate N₂O emissions in agriculture. *Life*, 12(3), 439.
7. IPCC. (2022). *Climate change 2022: Impacts, adaptation and vulnerability* (Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change). Cambridge University Press.
8. Karmakar, R., Das, I., Dutta, D., & Rakshit, A. (2016). Potential effects of climate change on soil properties: A review. *Science International*, 4, 51–73.
9. Klerkx, L., Jakku, E., & Labarthe, P. (2019). A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda. *NJAS: Wageningen Journal of Life Sciences*, 90–91, 100315.
10. Lal, R., Delgado, J. A., Groffman, P. M., Millar, N., Dell, C., & Rotz, A. (2011). Management to mitigate and adapt to climate change. *Journal of Soil and Water Conservation*, 66(4), 276–285.
11. Liakos, K. G., Busato, P., Moshou, D., Pearson, S., & Bochtis, D. (2018). Machine learning in agriculture: A review. *Sensors*, 18(8), Article 2674.
12. Patterson, L. A., Lutz, B., & Doyle, M. W. (2013). Climate and direct human contributions to changes in mean annual streamflow in the South Atlantic, USA. *Water Resources Research*, 49(11), 7278–7291.
13. Sparrow, R., & Howard, M. (2021). Robots in agriculture: Prospects, impacts, ethics, and policy. *Precision Agriculture*, 22, 818–833.
14. Vallero, D. A. (2019). Air pollution biogeochemistry. In *Air pollution calculations* (pp. 175–206). Elsevier.
15. Wolfert, S., Ge, L., Verdouw, C., & Bogaardt, M. J. (2017). Big data in smart farming – A review.

Agricultural Systems, 153, 69–80.