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Review article

Nexus between conservation agriculture and remote sensing: A review

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Abstract

Importance of the work: Remote sensing technologies can be effectively integrated into conservation agriculture practices to improve soil health, soil moisture and the sustainability of agricultural systems.

Objectives: To compile, analyze, and synthesize information and knowledge on the application of remote sensing technologies for evaluating soil health and productivity of agricultural crops under conservation practices.

Materials & Methods: A literature review of secondary data from journals and online reports was used to analyze the relationship between remote sensing and conservation agriculture. The benefits and challenges were reviewed of remote sensing technologies in agricultural management and the theoretical paradigms in conservation agriculture and environmental policy.

Results: Remote sensing technologies have the ability to collect data over large areas in a timely and cost-effective manner and to detect soil health and soil moisture, which in turn, can prevent pest outbreaks and diseases, resulting in increased crop yields. Researchers can utilize satellite imagery analysis to identify soil moisture levels to help farmers understand water dynamics and make decisions on irrigation scheduling, crop selection and soil conservation practices. This approach has been useful to farmers for planning water availability, adjusting irrigation schedules and implementing conservation practices to improve crop resilience and sustainability.

Main finding: Advances in remote sensing technology have resulted in more efficient and accurate methods for monitoring soil moisture and health. Increasing access to remote sensing data through open data initiatives has provided a wealth of benefits to the agricultural community.

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Introduction

Remote sensing technology has emerged as a powerful tool to revolutionize the way agriculture is practiced around the world. Conservation agriculture (CA) involves a farming system (such as no-till farming, cover cropping and agroforestry) that aims to improve soil health, maintain soil moisture levels, reduce erosion and increase biodiversity, since at least 45% of the soil surface is covered with crop residues (Sahu et al., 2020). Monitoring and predicting soil moisture patterns with remote sensing technology can help farmers better assess the effectiveness of conservation practices and make adjustments to improve their outcomes (Shanmugapriya et al., 2019; Weiss et al., 2020). For example, by monitoring soil moisture levels in no-till fields, farmers can ensure that the soil remains moist enough to support beneficial soil organisms and promote crop resilience. In addition, remote sensing technology can predict soil moisture patterns, which help farmers optimize their conservation practices and achieve better outcomes in terms of soil health, water conservation and crop productivity than physical, ground-based experimental methods, which are costly, laborious and time consuming.

The use of satellite imagery and ground-based sensors allows researchers and farmers to gather valuable data on soil moisture levels and make informed decisions to enhance crop production while minimizing environmental impact (Kingra et al., 2016). Soil moisture is a critical factor that influences crop growth, nutrient availability and water use efficiency in agricultural systems. Monitoring soil moisture levels help farmers and researchers understand the water dynamics of a field and make early decisions on irrigation scheduling, crop selection, soil conservation practices and pest and disease control mechanisms (Datta et al., 2017; Pereira et al., 2020). Researchers can gather soil moisture data remotely without physical contact, utilizing a range of platforms, including satellites, aircraft, drones and ground-based sensors. According to Tavakol et al. (2021), satellite imagery provides broad spatial coverage of soil moisture patterns across large agricultural landscapes, whereas ground-based sensors offer high-resolution data at specific locations. A combination of different remote sensing platforms can help researchers create detailed maps of soil moisture variability, crop management and pest and disease management for use in monitoring changes over time.

One of the key advantages of using remote sensing technology for monitoring soil moisture is its ability to provide real-time data on a large scale. With satellite imagery, researchers can track soil moisture variability at different spatial and temporal scales and identify areas of fields that are affected by pests and diseases (Mohanty et al., 2017). Remote sensing and computer vision have led to advances in the development of precision agriculture. This information can be used to identify areas of water stress, good irrigation management practice and improve water use efficiency, enabling farmers to make more informed decisions on improving soil moisture availability. Farmers can make timely decisions on crop management practices and reduce water usage while maintaining crop productivity (Kingra et al., 2016). In addition to monitoring soil moisture levels, remote sensing technology may predict soil moisture patterns and forecast future changes. Gaudin et al. (2015) reported actual yield percentages (root mean square errors), which ranged from 12% to 13% for soybean and 14% to 22% for wheat. Analyzing historical data and meteorological information helps researchers develop models that predict soil moisture dynamics under different climatic conditions (Cheng et al., 2022). These predictive models are useful for farmers to plan for future water availability, adjust irrigation schedules, identify pests and diseases and implement conservation practices to mitigate the impact of droughts and water scarcity.

Particulate matter (PM) ≤ 2.5 μm represents a critical component in conservation agriculture because of its impact on air quality, human health and soil health. Conservation agriculture practices, such as reduced tillage and cover cropping, help reduce PM 2.5 emissions by reducing soil disturbance, increasing soil organic matter and promoting the soil biota. Addressing PM 2.5 in conservation agriculture requires integrated strategies that balance soil health, air quality and agricultural productivity. This can be achieved through optimizing conservation practices, implementing PM 2.5 reduction technologies (such as mulching, cover crops and soil stabilization), enhancing soil carbon sequestration and promoting sustainable agricultural policies.

Precision agriculture is an approach to farm management that uses advanced technology and data analysis to enhance: crop health; variable input application rates (seeds, fertilizers, pesticides); precision irrigation; yields; and sustainability. Precision agriculture is a key component of the fourth agricultural revolution, with its adoption increasing globally, driving sustainable and efficient agricultural practices. Remote sensing technologies are used in both conservation agriculture and precision agriculture, but they are more suitable for conservation agriculture because of their lower cost and data integration. Remote sensing technologies are better suited for larger spatial scales, whereas precision agriculture focuses on individual fields or crops. While precision agriculture focuses on high-resolution data for precise crop management (productivity and efficiency), conservation agriculture leverages remote sensing technologies for broader landscape management and sustainability goals.

Materials and Methods

This review examines the application of remote sensing technology in conservation agriculture management, highlighting its role in promoting sustainable agricultural practices. The review explores the global context of remote sensing in agricultural management, including the legal framework, transformative pathways towards sustainability and the integration of remote sensing technology in conservation agriculture, as well as the underlying theoretical principles and paradigms that guide its implementation.

Results and Discussion

Global perspective of remote sensing in agriculture management

During the 2013/14 agricultural season, conservation agriculture was implemented on a substantial scale, encompassing over 157 million hectares of both rainfed and irrigated cropland (Kassam et al., 2021). Given the continued adoption and expansion of CA practices, it is probable that the current extent of CA spread exceeds 200 million hectares, although precise quantification requires updated data and verification. In the 2015/16 farming season, conservation agriculture accounted for 180 M ha or 12.5% of global cropland (Kassam et al., 2015). As the world population continues to grow, the demand for food is increasing at an unprecedented rate. However, traditional agricultural methods face various challenges, such as climate change, water scarcity and soil degradation. To meet the increasing demand for food while also addressing these challenges, innovative solutions are needed. By using satellite imagery, drones and other remote sensing technologies, farmers can monitor their fields more effectively, make informed decisions and increase productivity in a sustainable manner (Thenkabail et al., 2018). Approximately 51% of crop loss, accounting for USD 13.3 billion, is due to pest and disease attacks on crops in Africa (Mutanga et al., 2017). To address such losses, Zhang et al. (2019) utilized satellite imagery to monitor the growth of crops, detect pests and diseases and assess the impact of climate change on agricultural land (Fig. 1). Such actions have been reported to help farmers make timely decisions, such as adjusting irrigation schedules, regulating inputs, or taking preventive measures against pests and diseases and increasing the efficiency of their operations (Sishodia et al., 2020).

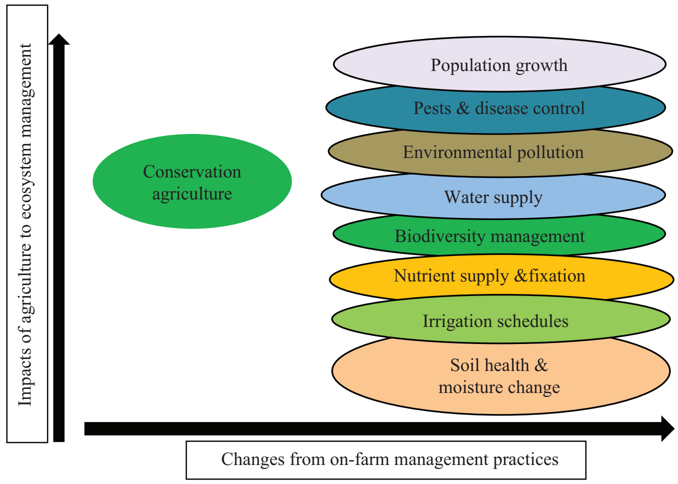

Fig. 1 Global perspective of remote sensing in agriculture management (Adapted from Zhang et al., 2019)

In addition to improving productivity, remote sensing technology helps farmers reduce environmental impact. Monitoring soil moisture levels and crop health helps farmers use resources more efficiently, reduce water usage and minimize the need for chemical inputs (Fritz et al., 2019; Weiss et al., 2020). Conservation agriculture saves 20–30% of irrigation water because of lower evapotranspiration losses from the surface, as it is covered with residues (Jat et al., 2020). This is useful in reducing the risk of soil degradation, water pollution and other environmental problems associated with conventional agriculture. AbdelRahman (2023), reported that approximately 50% of sub-Saharan agricultural land has lost productivity due to degradation, while 80% of the rangeland showed signs of degradation. Hossain et al. (2020) reported that agricultural land degradation was particularly high in the developing world, such as in Central America (75%), Africa (20%) and Asia (11%). Farmers can apply remote sensing technology to identify areas of their fields that are underperforming and take corrective actions to improve yields. Furthermore, remote sensing technology has changed the way agricultural data are collected and analyzed on a global scale (Zagade et al., 2018). The integration of satellite imagery with other data sources, such as weather data, soil data and market prices, has helped researchers and policymakers gain a better understanding of global agricultural trends for informed decisions on food security, poverty reduction and socio-economic and environmental issues.

The legal framework of conservation agriculture

Over the years, there has been a growing concern on sustainability and ethical farming practices, prompting governments around the world to introduce regulations that govern agricultural development. The legal framework surrounding agricultural practices is crucial to ensuring the protection of farmers, consumers and the environment. One of the main objectives of the legal framework in conservation agriculture is to promote sustainable farming practices that minimize the environmental impact of agriculture (Sahu et al., 2020). This includes regulations that govern the use of pesticides, fertilizers and genetically modified organisms. For example, in Zimbabwe, Zambia and Malawi, there are strict regulations on the use of dichlorodiphenyltrichloroethane, commonly known as DDT, that require farmers to adopt more sustainable farming methods, such as crop rotation and integrated pest management (IPM). These regulations aim to protect the soil, water and air from pollution and degradation while also ensuring the long-term viability of agricultural production (Piñeiro et al., 2020).

Additionally, the treatment of animals in the agricultural industry has prompted governments to introduce regulations that govern the housing, feeding and handling of livestock (Seufert et al., 2017). These regulations aim to ensure that animals are treated humanely and are not subjected to unnecessary suffering. New Zealand, Denmark and Norway have strict regulations that govern the use of antibiotics and hormones in livestock production, as well as regulations that protect animals from cruel and inhumane treatment. Additionally, the legal framework in conservation agriculture aims to protect the rights of farmers and consumers (Seufert et al., 2017). This includes regulations that govern the labeling and marketing of agricultural products, as well as regulations that protect farmers from unfair practices by agricultural corporations. For example, the USA, the Netherlands, South Africa and many other countries have introduced regulations that require food producers to label their products with information about their origin, production methods and ingredients. Knowledge of these items enables consumers to make informed choices about the food they eat and promote transparency in the agricultural sector.

However, enforcement mechanisms need to be strengthened to ensure that farmers and agricultural corporations comply with regulations. Additionally, there is a need for greater cooperation between governments, farmers and consumers to promote sustainable agricultural practices and address issues such as food security and climate change (Biswas et al., 2019).

Transformative pathways toward sustainable agriculture

Achieving sustainability in agriculture is a complex and multifaceted challenge that requires the implementation of transformative pathways because agriculture is not just about ensuring food security and economic growth, but also about preserving the environment, minimizing resource depletion and adapting to climate change. Achieving sustainability in agriculture requires considering various aspects, such as soil health, water conservation, biodiversity protection and climate resilience, which can be achieved through agroforestry, green manuring, intercropping, conservation tillage and biological agents (Fig. 2).

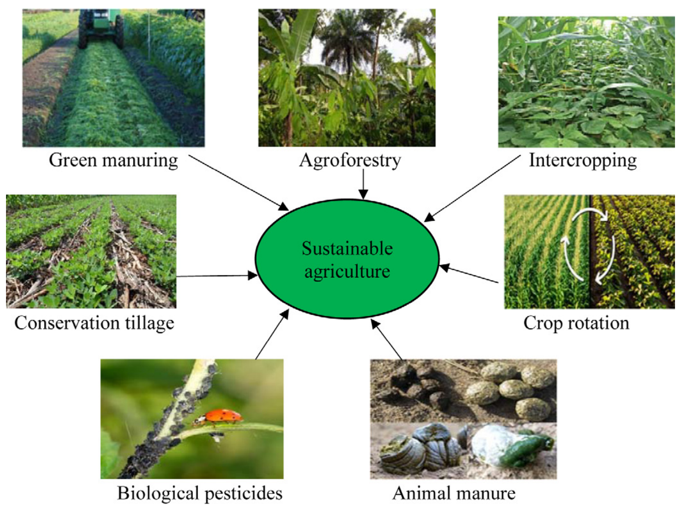

Fig. 2 Key pathways toward sustainable agriculture

Agroecology is a holistic approach to farming that seeks to mimic natural ecosystems and uses ecological principles to guide agricultural practices. This includes practices such as crop diversification, agroforestry, IPM and soil conservation techniques. Agroecology focuses on building healthy, resilient agroecosystems that can adapt to changing environmental conditions and reduce the need for external inputs such as chemical fertilizers and pesticides (Altieri, 2018). This not only increases biodiversity on farms, but also provides natural pest control and improves soil health.

Agroecology clearly increases yields, improves the quality of crops and reduces the environmental impact of agriculture. For example, a study conducted by Rajbhandari and Bhatta (2008) demonstrated a significant increase in total production of primary cereal crops (*Oryza sativa, Zea mays,* and *Triticum aestivum*) in Nepal during the 2008/09 agricultural season. Specifically, the implementation of agroecological practices resulted in a yield increase of over 50%, attributable to expanded cultivated area. Pretty (1999) reported that 95% of sustainable agriculture projects conducted in Africa have improved cereal yields by 50–80%.

Agroforestry and green manuring are two sustainable agricultural practices that have the potential to transform the way food is produced. Agroforestry involves integrating trees and shrubs into agricultural crops, providing multiple benefits, such as improved soil fertility, increased biodiversity, and enhanced resilience to climate change. On the other hand, green manuring involves the planting of cover crops that are later incorporated into the soil to improve its structure and fertility. A study conducted by Agbede (2018) in Nigeria during the 2015/2016 farming season on the use of agroforestry and green manures revealed that these technologies had a significant effect on the fresh root yield of cassava. Specifically, *Gliricidia* spp. increased the yield by 19%, *Moringa* spp. by 4%, *Leucaena* spp. by 1%, and *Azadirachta indica* (Neem) by 0.7%. Furthermore, in the following year, these treatments had an even greater effect on the fresh root yield of cassava; with *Gliricidia* spp. increasing the yield by 36%, *Moringa* spp. by 22%, *Leucaena* spp. by 19% and *Azadirachta indica* by 18%. These findings highlight the importance of utilizing agroforestry and green manures in agriculture to increase crop productivity. By adopting these practices, farmers can reduce their reliance on synthetic inputs, such as inorganic fertilizers and pesticides, leading to healthier soils and ecosystems (Majumder et al., 2021). Policymakers, researchers and farmers alike must support and promote these practices to create a more resilient food system for future generations.

Conservation agriculture focuses on reducing soil erosion, improving water use efficiency and maintaining soil health. This includes practices such as minimal soil disturbance, permanent soil cover and crop rotation. Permanent soil cover also helps protect the soil from erosion and maintain soil moisture levels for increased plant growth (Shrestha et al., 2020). In addition, this can help farmers adapt to climate change by increasing their resilience to drought conditions and extreme weather events. The adoption of CA can reduce farmers' reliance on external inputs and improve yields and the long-term sustainability of farming operations. Janousek et al. (2018) conducted a study that highlighted the potential effect of CA in reducing food waste on farms. Their findings indicated that implementing conservation agriculture practices led to a significant reduction (10–20%) in on-farm waste. These promising results indicate the role that sustainable farming practices can play in promoting more efficient uses of resources and minimizing environmental impact.

Intercropping is a traditional agricultural practice that has been used for centuries to improve soil fertility, increase crop yields and reduce reliance on pesticides (Fig. 2). The intercropping approach provides approximately 15–20% of the food supply globally (Altieri, 2018). In Latin America, approximately 70–90% of maize is intercropped with beans, potato and other crops, whereas 89% of cowpea in Africa and 90% of beans in Colombia are cultivated in intercrops (Patel et al., 2020). This practice helps maximize land use efficiency by allowing farmers to grow multiple crops in the same space. This increases the overall crop productivity and diversifies farm income. Additionally, intercropping help to increase soil fertility by varying the root depth, nutrient requirements and growth patterns of different crops. For example, leguminous plants, such as beans, groundnuts and soybean, can fix nitrogen in the soil (Kebede, 2021). Intercropping of grain legumes, such as cowpea with maize, increases nitrogen (N) cycling through biological N_2 fixation (Namatsheve et al., 2021). The incorporation of legume residue adds approximately 50–60 kg/ha of N to the soil that can be used by the succeeding crop (Jena et al., 2022). Consequently, this agricultural technology is useful in reducing pest and disease pressure by disrupting the lifecycle of pests and providing natural pest control through biodiversity. Deep-rooted crops help break up compacted soil layers and improve water infiltration. For example, grass species such as *Brachiaria* have demonstrated enormous potential for reducing water losses due to leaching because of their deep-root architecture (Rosolem et al., 2017).

Crop rotation is an important practice for sustainable agriculture that involves planting different crops in a sequence on the same piece of land. Like intercropping, crop rotation is crucial for improving soil structure, increasing nutrient availability and reducing the buildup of pests and diseases. By alternating crops with different nutrient requirements and growth habits, farmers can prevent soil depletion and maintain soil fertility over time. Gaudin et al. (2015) reported that cultivation of soybean after the alteration of corn with the integration of reduced tillage improved the production of corn and soybeans by 7% and 22%, respectively. Similarly, planting legumes, such as peas or beans, in rotation with cereals, such as wheat or corn, can help replenish nitrogen levels in the soil and reduce the need for synthetic fertilizers. Crop rotation can also disrupt pest and disease cycles by interrupting the host plants on which certain pests and diseases thrive. A 7 yr diverse crop rotation study by Pandey and Shrestha (2021) in Nepal, involving 3 yr of alfalfa, 2 yr of chili pepper and 2yr of cotton, helped break the disease cycle and increased crop productivity. All three plants belonged to different crop families, which helped disrupt the disease cycle and increased crop productivity.

Manuring, or the application of organic matter to the soil, is also an essential practice for sustainable agriculture. Manures are rich sources of nutrients, organic matter and beneficial microorganisms that can improve soil structure, fertility and water-holding capacity. Farmyard manure is a heterogeneous mixture of solid and liquid excreta of farm animals along with the crop residue that remains after cattle feeding. By recycling organic wastes, such as crop residues, animal manures and compost back into the soil, farmers can reduce the need for chemical fertilizers and improve soil health. Cattle manure contains approximately 0.5–1.5% N, 0.4–0.8% P_2O5 and 0.5–1.9% K_2O, which are involved in nutrient cycling, soil aeration and pest regulation (Alhrout et al., 2018).

Remote sensing technology in water-energy-food nexus of conservation agriculture

The water-energy-food nexus refers to the interconnected nature of water, energy and food resources, emphasizing the need for integrated solutions to ensure the sustainable management of these resources (Simpson and Jewitt, 2019). As the demand for water, energy and food increases, the pressure on these resources intensifies, leading to competition, conflicts and trade-offs among them (Simpson and Jewitt, 2019). For example, water is needed for energy production (hydropower, cooling in thermal power plants) and food production (irrigation), whereas energy is required for water supply (pumping, treatment works) and food production (mechanized farming, processing), as shown in Fig. 3. Similarly, food production consumes water and energy resources, while its waste adds pressure to water resources and contributes to pollution and greenhouse gas emissions. Field evidence has shown that targeted CA based management practices have the potential to produce more food (10–15%) from less water (20–75%) and less energy (20–45%) while lowering the carbon footprint by 25–30% (Jat et al., 2020). A meta-analysis of CA based practices in South Asia revealed a mean yield advantage of 5.8%, with a 12.6% higher water use efficiency and a 12–33% lower global warming potential, which could be attributed to the efficient use of water, energy and fertilizer (Jat et al., 2020). However, the increased demand for water, energy and food often leads to the degradation of ecosystems through pollution, deforestation, overexploitation of resources and climate change (Sishodia et al., 2020). Researchers and practitioners can utilize satellite imagery, drones and other remote sensing tools to monitor changes in water availability, energy and food production systems.

For example, researchers can use satellite imagery analysis to identify areas of high water consumption and develop targeted strategies to improve water efficiency (Sowmya et al., 2017). Similarly, remote sensing technology can help identify suitable locations for renewable energy development, such as solar and wind farms, on the basis of factors such as solar radiation and wind patterns. Researchers can integrate satellite imagery and other data sources to identify areas at risk of pest infestations and develop early warning systems to minimize crop damage (Weiss et al., 2020). This proactive approach not only improves food security but also reduces the need for chemical pesticides, benefiting both the environment and human health. Overall, remote sensing technology offers a powerful toolkit for addressing the complex challenges of the water-energy-food nexus and conservation agriculture (Simpson and Jewitt, 2019).

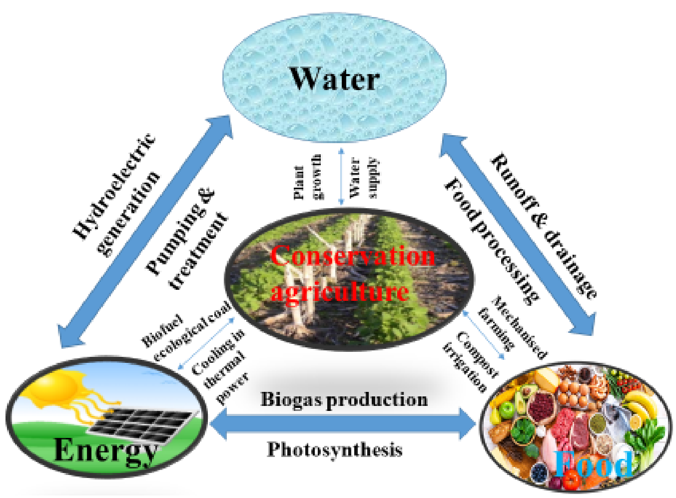

Fig. 3 Water-energy-food nexus of conservation agriculture (Adapted from Gulati et al. (2013))

Drivers of conservation agriculture

Research and development have always played crucial roles in shaping the future of agriculture. With the world population expected to reach 9.7 billion by 2050, the need for sustainable agricultural practices has become more pressing than ever before (Shrestha et al., 2020). The adoption of conservation agriculture has proven to benefit farmers in various ways, including increased crop yields, reduced production costs and improved resilience to climate change (Shrestha et al., 2020). However, the widespread adoption of CA faces several challenges, including knowledge gaps, limited access to technologies and a lack of institutional support. Agricultural research and development can play a pivotal role in overcoming these challenges by generating scientific knowledge, developing innovative technologies and providing extension services to farmers. According to Shah et al. (2017), through targeted research efforts, agricultural scientists can identify best practices for CA, assess the impact of different management strategies on crop productivity and soil health and develop new technologies to enhance its adoption.

Traditional tillage practices, such as plowing and harrowing, can lead to soil erosion, nutrient loss and reduced soil fertility (Seufert et al., 2017). Conservation tillage systems, such as no-till and reduced-till systems, have greater benefits in terms of agricultural management. Research has shown that conservation tillage can significantly increase crop productivity and sustainability by 10–15% through the rejuvenation of soil fertility (Patel et al., 2020). Integrated pest management practices, such as the use of biological control agents and pheromone traps, help farmers reduce their reliance on synthetic pesticides and promote natural pest control mechanisms. However, investing in agricultural research and development is essential to support the adoption of CA and ensure sustainable food production systems (Jat et al., 2020). Governments, research institutions and private sector organizations need to prioritize funding for research programs that support conservation agriculture, disseminate knowledge to farmers and promote the adoption of sustainable farming practices. Capacity-building initiatives, such as training programs, field demonstrations and extension services, are useful means for farmers to learn about the benefits of CA and provide them with the necessary skills and tools to implement these practices on their farms.

Benefits of using remote sensing technology in conservation agriculture

Farmers use remote sensing technology to monitor the health of their crops and detect any signs of disease or stress before it becomes a widespread problem (Zagade et al., 2018). This allows for timely interventions such as the application of pesticides or fertilizers to prevent crop loss and ensure a relatively high yield. When farmers know exactly when and how much water to apply in irrigation, they can reduce water wastage and increase the overall yield (Datta et al., 2017; Mohanty et al., 2017). This is important in dry regions where water resources are limited and where conservation is critical for sustainable agriculture. This allows for targeted application of fertilizers or soil amendments to improve soil quality and optimize crop growth. Furthermore, remote sensing technology helps reduce labor, fuel and input costs through data-driven decision making. Conservation agriculture eliminates power-intensive soil tillage work, reducing the drudgery of such strenuous work as well as the number of laborers involved in crop production by more than 50%, while reducing fuel requirements by approximately 70% and the need for machinery by approximately 50% (Kassam et al., 2015). Chuvieco (2020) noted that the analysis of images taken at different stages of crop growth enables farmers to track the progress of their crops and make informed decisions about when to apply additional inputs or to harvest. This can lead to more efficient crop management practices and better yields. A study by Fritz et al. (2019) revealed that remote sensing technology is crucial in land use planning for the identification of suitable land for cultivation, conservation and other uses. Altieri (2018) and Chuvieco (2020) reported that by leveraging remote sensing technology, farmers and agricultural stakeholders can increase productivity by 20% and sustainability and profitability by 25%, ultimately contributing to food security.

The development of agricultural policies is highly important for ensuring the sustainability and success of the sector. However, the process of developing agricultural policies involves a wide range of stakeholders who have varying interests and perspectives. Governments play a central role in setting policies that govern agricultural practices, trade and subsidies (Indraningsih et al., 2021). They are responsible for creating a conducive environment for agricultural development, ensuring food security and addressing issues such as climate change and sustainability. Government officials, including policymakers and regulators, work closely with other stakeholders to develop, implement and monitor agricultural policies.

Zimbabwe has an agrarian society, with more than 60% of population being dependent on land and agriculture; consequently, farmers, agricultural workers and agribusinesses have a major stake in the development of policies that affect their livelihoods and businesses (Indraningsih et al., 2021). They provide valuable insights and expertise on agricultural practices, market trends and technological advancements that can inform policy decisions. Environmental and conservation groups advocate for policies that promote environmental sustainability, the conservation of natural resources and the protection of biodiversity (Indraningsih et al., 2021). They raise awareness of the impact of agriculture on the environment, such as deforestation, water pollution and habitat destruction, and advocate for policies that mitigate these negative impacts. They develop and implement policies that balance the needs of agriculture with environmental protection.

Academia and research institutions also help in the development of remote sensing technology training. They provide valuable expertise, data and analysis on agricultural issues that inform policy decisions. Scientists and researchers have studied agricultural practices, technologies and trends to identify best practices (Indraningsih et al., 2021). South Africa has one of the highest rates of public investment in education in the world, with 5.3% of its gross domestic product and 20% of total state expenditure being spent on education (Burger and Calitz, 2019). Formal education in agriculture is offered by 12 colleges of agriculture, 6 universities of technologies and 11 universities offering various tertiary agricultural education training programs that are nationally accredited (Academy of Science of South Africa, 2017). Non-formal agricultural education is offered by a range of providers, including: public agricultural extension and training services; providers in non-governmental organizations and the private sector; and by universities, colleges and some agricultural high schools (Academy of Science of South Africa, 2017). Training agricultural professionals increases the skills of extension staff; however, the lack of continuing education opportunities could constitute a drawback to agricultural extension agents' performance impacting on food security (Raidimi and Kabiti, 2019).

Challenges of remote sensing technology in agriculture management

There are still major challenges that must be considered when remote sensing technologies are adopted, particularly the high cost for applications in CA (Thenkabail et al., 2018; Zagade et al., 2018). The initial investment in purchasing sensors, drones, satellite imagery and software can be prohibitively expensive for many rural poor farmers, especially those in developing countries or in small-scale operations. Additionally, there are ongoing costs for maintenance, training and updating software, which can further strain farmers with limited budgets (Sishodia et al., 2020). This financial barrier can prevent farmers from utilizing remote sensing technology to its full potential, limiting their ability to apply precise conservation practices and maximize yields. Similarly, another limitation can be reliance on external data sources such as satellite imagery or weather forecasts. Sowmya et al. (2017) revealed that farmers may face challenges related to data accuracy, resolution or timeliness, which can impact the effectiveness of their decision-making processes. In some cases, agricultural fields (and especially irrigated fields) are highly dynamic because each field may be at a different stage of development and thus subject to confusion with natural land cover classes.

Accessibility is another key limitation in the widespread adoption of remote sensing technology in conservation agriculture. Many farmers may not have the technical expertise or access to the reliable internet connectivity required to collect, analyze and interpret remote sensing data effectively (Thenkabail et al., 2018). Without proper training and resources, farmers often struggle to navigate complex software or interpret the data accurately, leading to suboptimal decision-making in their agricultural practices. Furthermore, in remote or rural areas, where connectivity is limited, accessing real-time satellite images or drone footage may be challenging, hindering farmers' ability to monitor their fields and make timely adjustments to their conservation practices (Chuvieco, 2020). Data interpretation is a critical aspect of using remote sensing technology in conservation farming. The abundance of raw data collected from sensors, drones or satellites can be overwhelming and difficult to interpret without the necessary expertise. However, farmers need to possess knowledge of crop physiology, soil science and remote sensing techniques to accurately analyze and apply the data to various farming practices. Additionally, the accuracy and reliability of remote sensing data can be influenced by factors such as weather conditions, cloud cover or sensor calibration, which can further complicate the interpretation process (Thenkabail et al., 2018).

Challenges in agricultural policy development and suggested actions

Agriculture is faced with numerous and varied factors, ranging from environmental concerns to economic limitations.

To address these challenges and create effective policies, it is important for policymakers to consider a range of factors and potential solutions. One of the major challenges in agricultural policy development is the issue of sustainability (Michler et al., 2019). With the growing need to feed a rapidly expanding global population, agricultural practices have become increasingly intensive, leading to negative environmental impacts such as soil erosion, water pollution and loss of biodiversity. Thus, policymakers need to find ways to promote sustainable agricultural practices that are both environmentally friendly and economically viable. One suggested action to promote sustainability in agricultural policy development is to incentivize farmers to adopt practices that minimize their environmental impact (Michler et al., 2019). With the provision of financial incentives for sustainable practices, policymakers can encourage farmers to adopt more environmentally friendly methods of agricultural production.

Another challenge in agricultural policy development is the issue of food security. With climate change and other environmental factors posing a threat to global food production, it is essential for policymakers to find ways to ensure that all populations have access to a sufficient and nutritious food supply (Sahu et al., 2020; Shrestha et al., 2020). This is important in developing countries such as Somalia, Nigeria and Zimbabwe, where many people are already living in poverty and facing food shortages on a regular basis. Sahu et al. (2020) considered that to address food security challenges, policymakers should consider a range of actions, including increasing investment in rural infrastructure, promoting access to credit for small-scale farmers and developing early warning systems for food crises. Investing in these areas could help policymakers build a more resilient food system that is better able to withstand the challenges of climate change and other environmental threats.

Agricultural policy development is also constrained by market access. In many developing countries such as Zimbabwe, small-scale farmers struggle to access markets due to the lack of infrastructure, limited financial resources and unfavorable trade policies (Ndlovu and Masuku, 2021). This can be difficult for farmers to sell their produce at a fair price, leading to reduced income and economic insecurity. According to Chuvieco (2020), offering workshops, demonstrations and hands-on training sessions help farmers gain the knowledge and confidence needed to effectively utilize remote sensing technology in agriculture management. Furthermore, policymakers and development agencies need to invest in infrastructure improvements, such as expanding broadband internet access, establishing data-sharing platforms, or subsidizing the cost of remote sensing equipment, to increase the accessibility and affordability of these technologies for all farmers.

Successful integration of remote sensing in agriculture for climate resilience

Climate change has become a pressing concern worldwide, with implications for various sectors of the economy, including agriculture. One of the primary impacts of climate change on agricultural productivity is the increase in extreme weather events such as droughts, floods and heatwaves (Malhi et al., 2021). These events may have devastating effects on crop yields, leading to reduced production and food shortages. For example, prolonged droughts can lead to water stress in crops, affecting their growth and development. Similarly, floods can wash away crops and soil nutrients, causing significant losses for farmers (Baba and Adamu, 2021). In addition to extreme weather events, climate change affects the distribution and growth of pests and diseases in agricultural crops. Plant diseases are estimated to cause yield reductions of almost 20% in principal food and cash crops worldwide (Baba and Adamu, 2021). In Asia, the agricultural sector faces significant economic challenges due to the adverse effects of pests and diseases. According to Oerke et al. (2012), it is estimated that approximately 14.2% of potential agricultural production is lost annually as a direct consequence of these biotic stressors. This figure translates to an economic loss of approximately USD 43.8 billion, highlighting the substantial impact that pests and diseases have on agricultural productivity in the region.

Warm temperatures and changing precipitation patterns create favorable conditions for pests to thrive, leading to increased crop damage. It is estimated that more than 80% of total global crop production is supplied by rainfall; therefore, changes in total seasonal rainfall or its patterns are very important (Tavakol et al., 2021). For example, the spread of diseases, such as wheat rust and coffee leaf rust, has been attributed to climate change, posing a major threat to crop production. Changes in precipitation patterns and rising temperatures alter the water cycle, leading to changes in groundwater levels, surface water availability and irrigation practices (Baba and Adamu, 2021). This can result in water scarcity, affecting crop growth and productivity.

Farmers need to adapt to climate change and enhance agricultural productivity through climate-smart agricultural practices that are resilient to changing climatic conditions.

These practices not only help mitigate the impacts of climate change but also enhance the overall sustainability and resilience of agricultural systems. Furthermore, policymakers need to support farmers in adopting climate-smart agricultural practices through incentives, subsidies and extension services. Investing in research and innovation to develop new varieties of crops that are resilient to climate change and pests is also crucial for ensuring food security in the face of a changing climate (Malhi et al., 2021). Additionally, governments, research institutions and private companies should collaborate to address the implications of climate change for agricultural productivity and develop user-friendly software platforms and data visualization tools that simplify data interpretation and decision-making for farmers. Knowledge sharing among farmers, extension agents and agricultural experts can exchange best practices and success stories in the use of remote sensing technology for climate resilient agriculture (Weiss et al., 2020). One successful example of remote sensing technology being used for conservation agriculture is the monitoring of soil health and moisture levels. The Fondazione Edmund Mach (FEM) in Italy has developed a system called "SOILMAP," which uses satellite imagery and ground sensors to monitor soil moisture levels and nutrient content in vineyards (Puig-Sirera et al., 2021).

Another case study that demonstrates the successful integration of remote sensing technology in conservation agriculture involves the use of drones for precision agriculture. In Kenya, the Kenya Agricultural and Livestock Research Organization (KALRO) has been using drones equipped with cameras and sensors to monitor and map crop health and identify areas of pest infestation (Edmeades et al., 2017). By using these data, farmers were able to target their pesticide applications more precisely, reducing the amount of chemicals used and minimizing the impact on the environment. The World Agroforestry Centre (ICRAF) has used satellite imagery and ground sensors to monitor water levels in irrigation systems and natural water sources, such as rivers and lakes in Southeast Asia (Lin et al., n.d.). A 15 yr-old field in an agroforestry system showed a remarkable increase in carbon sequestration from 30–70%, with a rate of 4.4–10 t C/ha/yr (Patel et al., 2020). Farmers were able to conserve water resources more effectively, especially in water-stressed regions.

Theoretical paradigms in conservation agriculture and environmental policy

Theoretical paradigms in conservation agriculture and environmental policy play a major role in shaping how agricultural management approaches are related to sustainability, land management and ecosystem conservation (Fig. 4). Environmental policy refers to the set of laws, regulations and guidelines that govern environmental protection and sustainable development. One of the key theoretical paradigms in conservation agriculture is the agroecological approach, which emphasizes the importance of understanding the ecological interactions between crops, soil and the environment (Altieri, 2018). This approach highlights the interconnectedness of agricultural systems and aims to optimize the use of ecological processes to increase productivity and environmental sustainability. Agroecology promotes practices, such as crop rotation, intercropping and the use of cover crops, to improve soil health, conserve water and reduce the need for chemical inputs (Temegne et al., 2021). This paradigm recognizes the complex relationships among humans, agriculture and the environment and emphasizes the need for holistic and integrated approaches to land management.

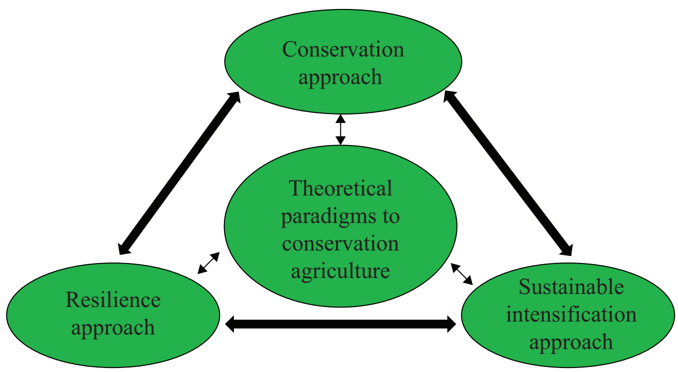

Fig. 4 Theoretical paradigms for conservation agriculture

Another important theoretical paradigm in conservation agriculture is the sustainable intensification approach, which seeks to increase agricultural productivity while minimizing environmental impacts (Jat et al., 2020). This paradigm recognizes the challenges of feeding a growing population while safeguarding the environment and natural resources. Sustainable intensification promotes practices such as precision agriculture, IPM and agroforestry to optimize yield while minimizing inputs and reducing greenhouse gas emissions.

In 2007, in Uttarakhand state, sustainable intensification methods for finger millet on a Himalayan foothill increased yields by 33% compared with those of the same variety grown under usual methods (Adhikari et al., 2018). In Nepal, the sustainable intensification approach increased finger millet yield by 82% compared with direct seeding and was 25% more than from transplanting with older seedlings (Bhatta et al., 2017). This approach acknowledges the trade-offs between productivity and sustainability and seeks to find a balance that ensures food security without compromising the health of ecosystems. In terms of environmental policy, one of the key theoretical paradigms is the precautionary principle, which emphasizes the need to take preventive measures to protect the environment even in the face of scientific uncertainty (Hansson, 2020). This principle suggests that if there is a risk of substantial harm to the environment, action should be taken to prevent it, even if the exact nature and extent of the harm are not fully understood. This paradigm underscores the importance of proactively addressing environmental risks and uncertainties to safeguard the health and integrity of ecosystems.

Lastly, the resilience approach forms the third theoretical paradigm, which focuses on building the capacity of agroecosystems to withstand and recover from disturbances and shocks (Walker and Salt, 2012). This approach recognizes the dynamic and adaptive nature of ecosystems and emphasizes the need to promote biodiversity, connectivity and ecosystem services to increase resilience. The resilience paradigm emphasizes the importance of maintaining agroecosystem functions and processes to ensure long-term sustainability and adaptability in the face of changing environmental conditions. This approach has been increasingly incorporated into policy frameworks and management strategies to support the resilience of ecosystems and communities in the face of climate change, land degradation and other threats.

Conclusions

The adoption of remote sensing in monitoring conservation agricultural practices has helped farmers promote more sustainable and resilient agricultural systems. Integrating diverse theoretical perspectives and strategies has led to a more sustainable and equitable future for agriculture and the environment. Similarly, agricultural research and development have served as drivers for CA by generating scientific knowledge, developing innovative technologies and providing extension services to farmers. Investing in research programs that support conservation agriculture, governments and organizations have helped farmers improve soil health, increase crop productivity and promote environmental sustainability. As such, innovative developments, including user-friendly platforms, enhance spatial and temporal resolution and promote public–private partnerships among agricultural organizations. The legal framework in conservation agriculture has been essential for promoting sustainable farming practices, protecting animal welfare and ensuring the rights of farmers and consumers.

Agricultural policy development is a complex and challenging process that requires policymakers to consider a wide range of factors and potential solutions. It involves a diverse range of stakeholders who are involved in shaping the future of the agricultural sector. While remote sensing technology offers tremendous potential for enhancing CA practices, there are many challenges and limitations that must be addressed to facilitate its widespread adoption. Climate change poses major challenges to agricultural productivity, with implications for global food security. Adopting climate-smart agricultural practices and implementing policies to support farmers in adapting to climate change are essential for ensuring sustainable agricultural production in a changing climate. To fully harness the power of remote sensing technology, researchers and farmers should improve data analysis capabilities such as crop stress detection and soil monitoring. However, remote sensing technology remains a valuable tool for addressing the interconnected challenges of the water-energy-food nexus and climate change and encouraging data sharing, standardization and privacy regulations.

Recommendations for remote sensing technology and conservation agriculture

More accurate predictions for crop yields, soil health and pest infestations should be obtained from extracting valuable insights from the vast amount of data that can be collected through remote sensing. Additionally, integrating remote sensing data with other sources, such as field measurements and modeling, should be a priority to provide a more comprehensive picture of agricultural technology. A more holistic understanding of the factors that influence crop growth should be developed by combining different types of data. Making data freely available to the public fosters collaboration and innovation, leading to new insights and discoveries that can benefit farmers around the world.

To increase farmer adoption, farmers should be rewarded for their conservation efforts to build a strong network of advocates for sustainable agricultural practices. Additionally, establishing policy frameworks for the use and sharing of remote sensing data and supporting research and development should be considered in enabling farmers to have increased knowledge of their agricultural practices. Offering extension services to train farmers in remote sensing and conservation agriculture is critical for capacity building. Encouraging public–private partnerships should be seen as a valuable avenue for driving innovation and investment in the use of remote sensing technology in agriculture. Similarly, standards and protocols for data collection and analysis should be fully developed to ensure that remote sensing data are collected and analyzed in a standardized and reliable manner.

Recommendations for future research

This study recommends the promotion of sustainable agricultural practices and environmental stewardship. The potential effects should be investigated of drone-based remote sensing for precision CA through high-resolution monitoring of crop growth, soil moisture and nutrient status. Specifically, in Zimbabwe, while assessing the economic benefits of remote sensing technology in CA remains key, conducting cost-benefit analyses to determine the financial viability of remote sensing technology adoption in agriculture should be studied.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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